

# Improved Baseflow Forecasting

Thanks to my committee:

Dr. Gary S. Johnson, University of Idaho  
**(Major Professor)**

## **Committee Members**

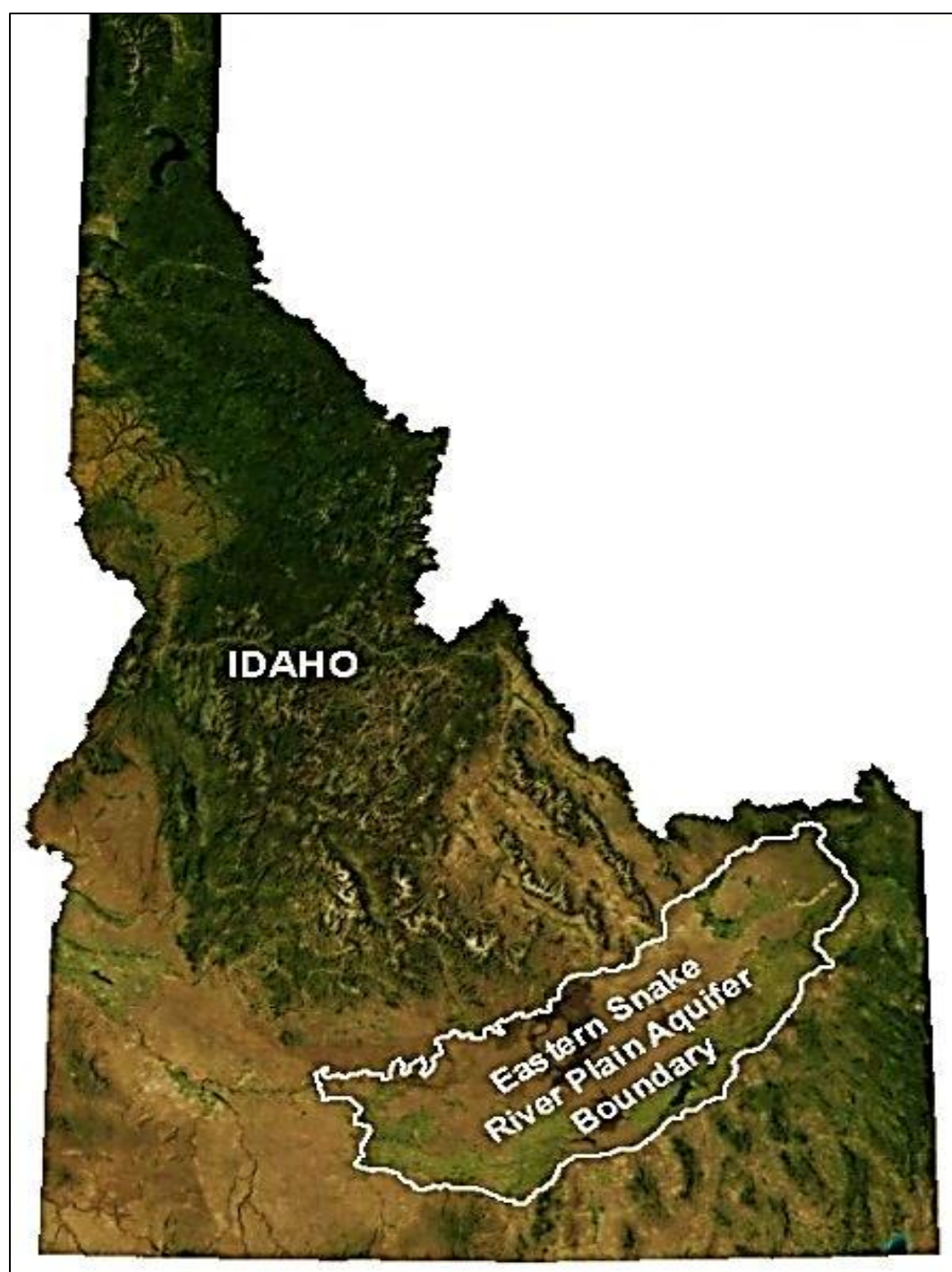
Dr. James R. Bartolino, USGS

Dr. Jerry Fairley, University of Idaho

Dr. Rob Van Kirk, Humboldt State University

# Research Goal

- Develop and evaluate methods to improve spring discharge forecasts.

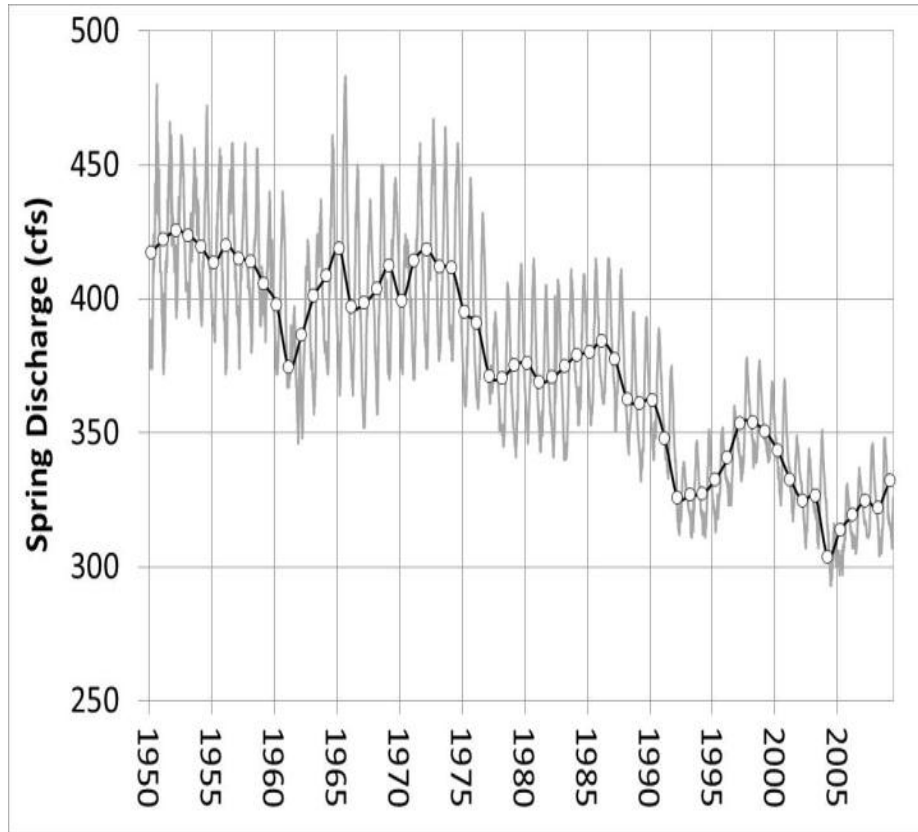




A satellite map showing a rugged, mountainous landscape. A white outline delineates a specific region in the center-right of the image. This region contains several dark, irregularly shaped features, likely lakes or wetlands, interspersed with green, forested areas. The surrounding terrain is characterized by steep, rocky slopes with sparse vegetation. The text 'Thousand Springs Complex' is located in the bottom-left corner, with a thin white line pointing from the text to the outlined area.

Thousand  
Springs  
Complex

# Thousand Springs

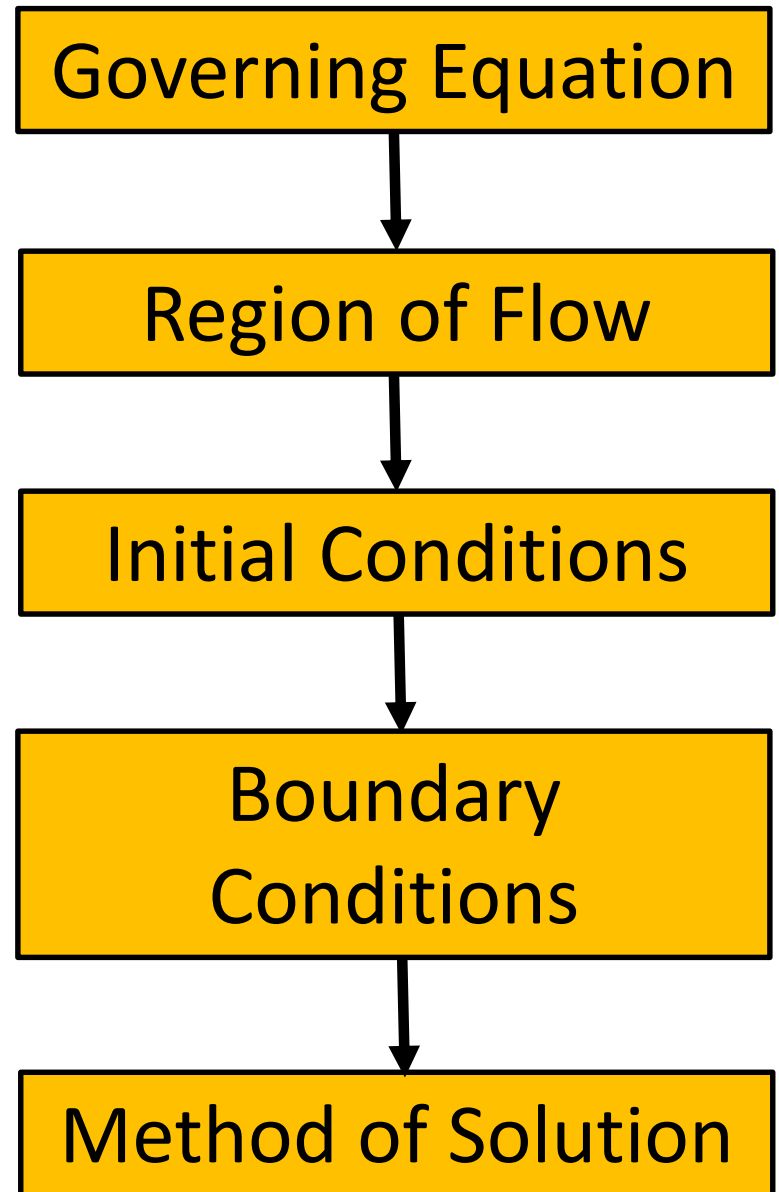


# Presentation Organization

- Research Motivation
- Forecasting Methods
  - **Analytical** (JAWRA, 2010, Vol. 46, No. 6, Pgs: 1116-1132)
  - **Statistical** (manuscript to be submitted for review)
  - **Numerical** (manuscript to be submitted for review)
- Conclusions

# Chapter 1. Analytical Approach

# Boundary Value Problem Solution Process



# Governing Equation

Horizontal flow in an unconfined, isotropic, homogeneous aquifer:

$$S_y \frac{\partial h}{\partial t} = K \left[ \frac{\partial}{\partial x} \left( h \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( h \frac{\partial h}{\partial y} \right) \right] + w(x, y, t)$$

Governing Equation

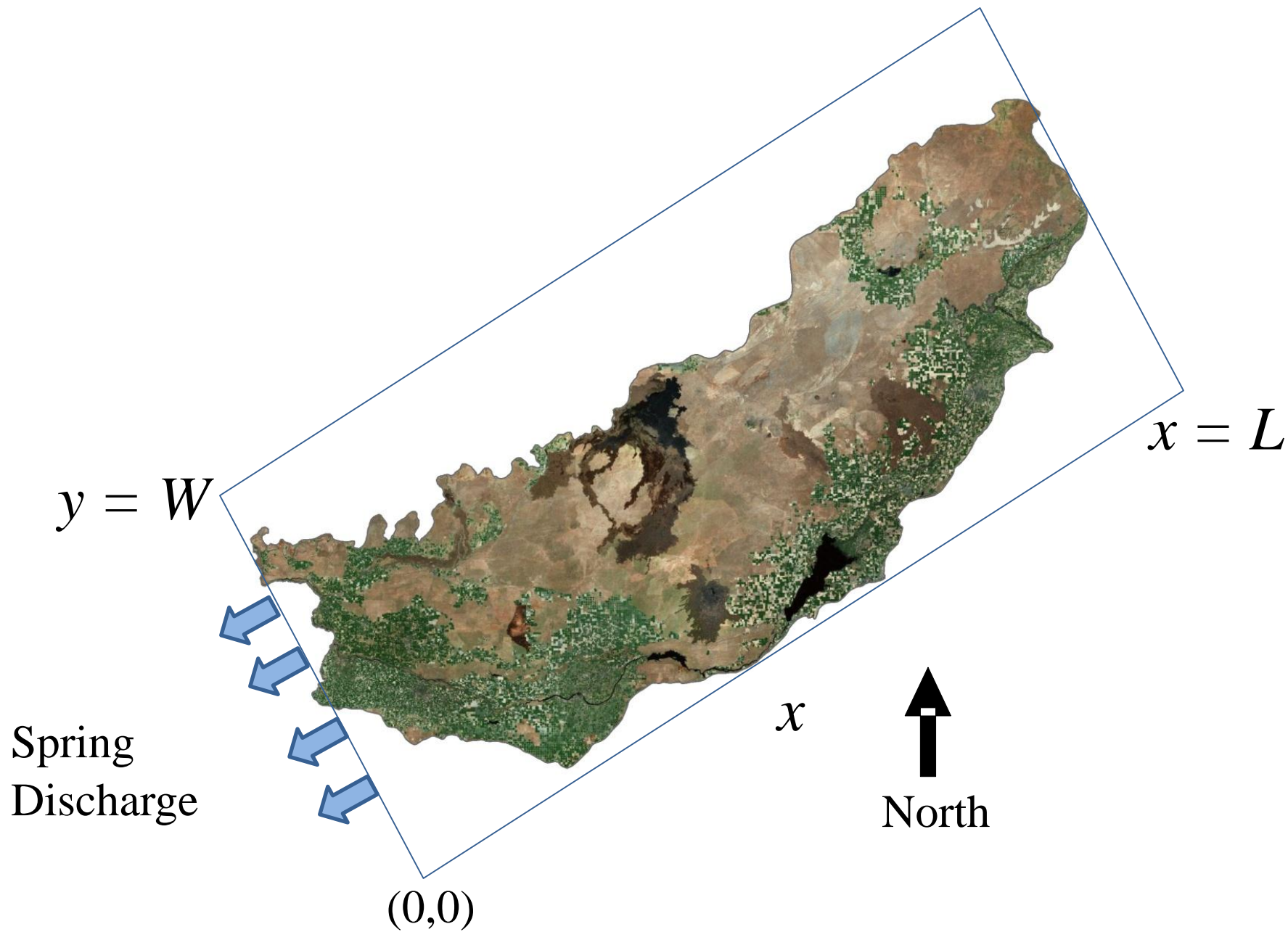
```
graph TD; A[Governing Equation] --> B[Region of Flow]; B --> C[Initial Conditions]; C --> D[Boundary Conditions]; D --> E[Method of Solution];
```

Region of Flow

Initial Conditions

Boundary  
Conditions

Method of Solution



- Established boundary and initial conditions
- Used Darcy's law to develop a general form of recharge/discharge equation for total discharge from aquifer
- Method of Solution: Fourier series

# Fourier Series for Aquifer Discharge

$$Q(t) = \pi \frac{D}{L^2} \sum_{n=1}^{\infty} (2n-1) \underbrace{\left[ \int_0^t \exp\left( \frac{-(2n-1)^2 \pi^2 D}{4L^2} (t-s) \right) f(s) ds \right]}_{\text{}} \sin \frac{(2n-1)\pi r}{2L}$$

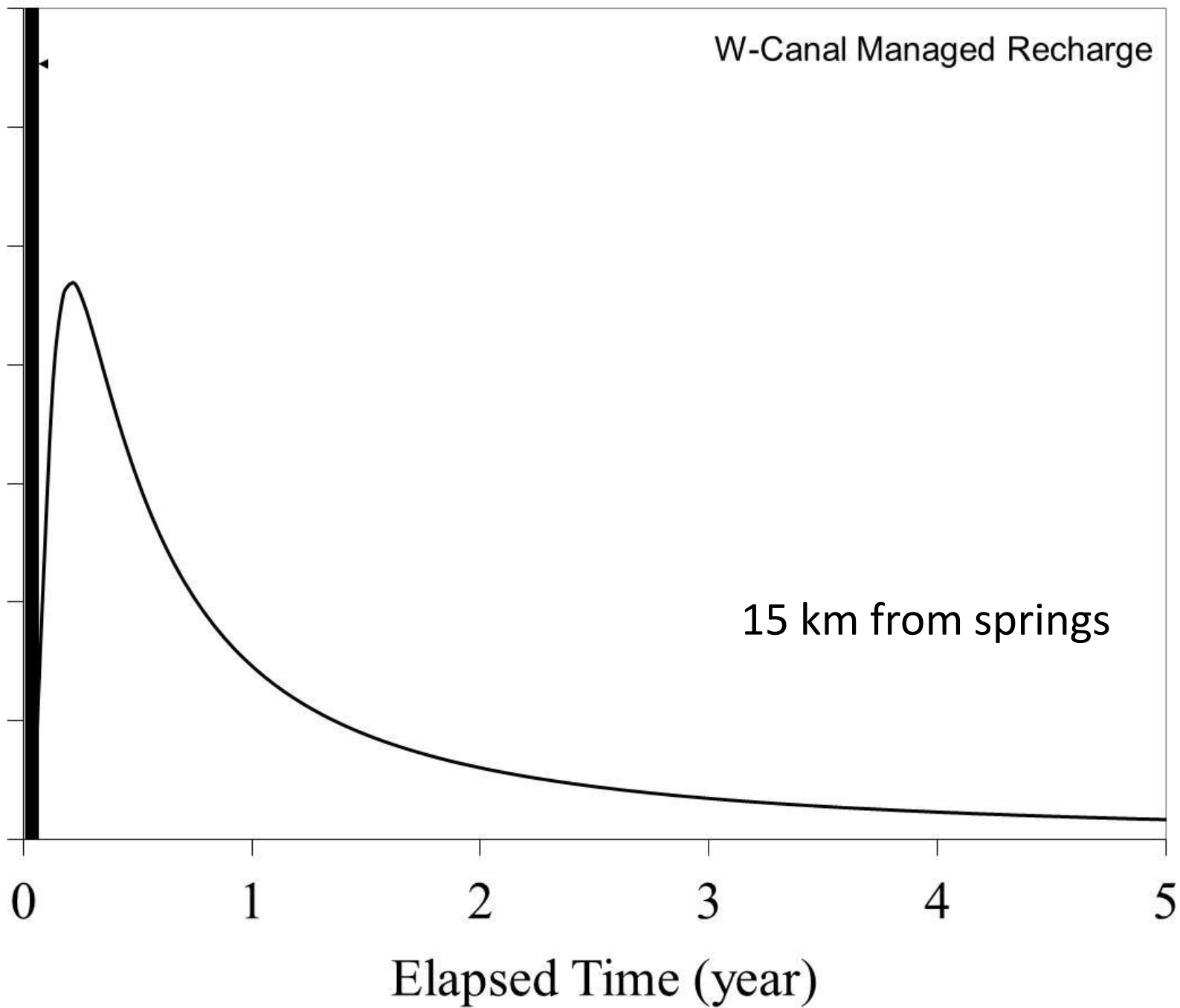
# What do we put in for recharge?

- Use common forms of recharge:
  1. Instantaneous events (Type 1)
  2. Recharge that is periodic in time (Type 2)

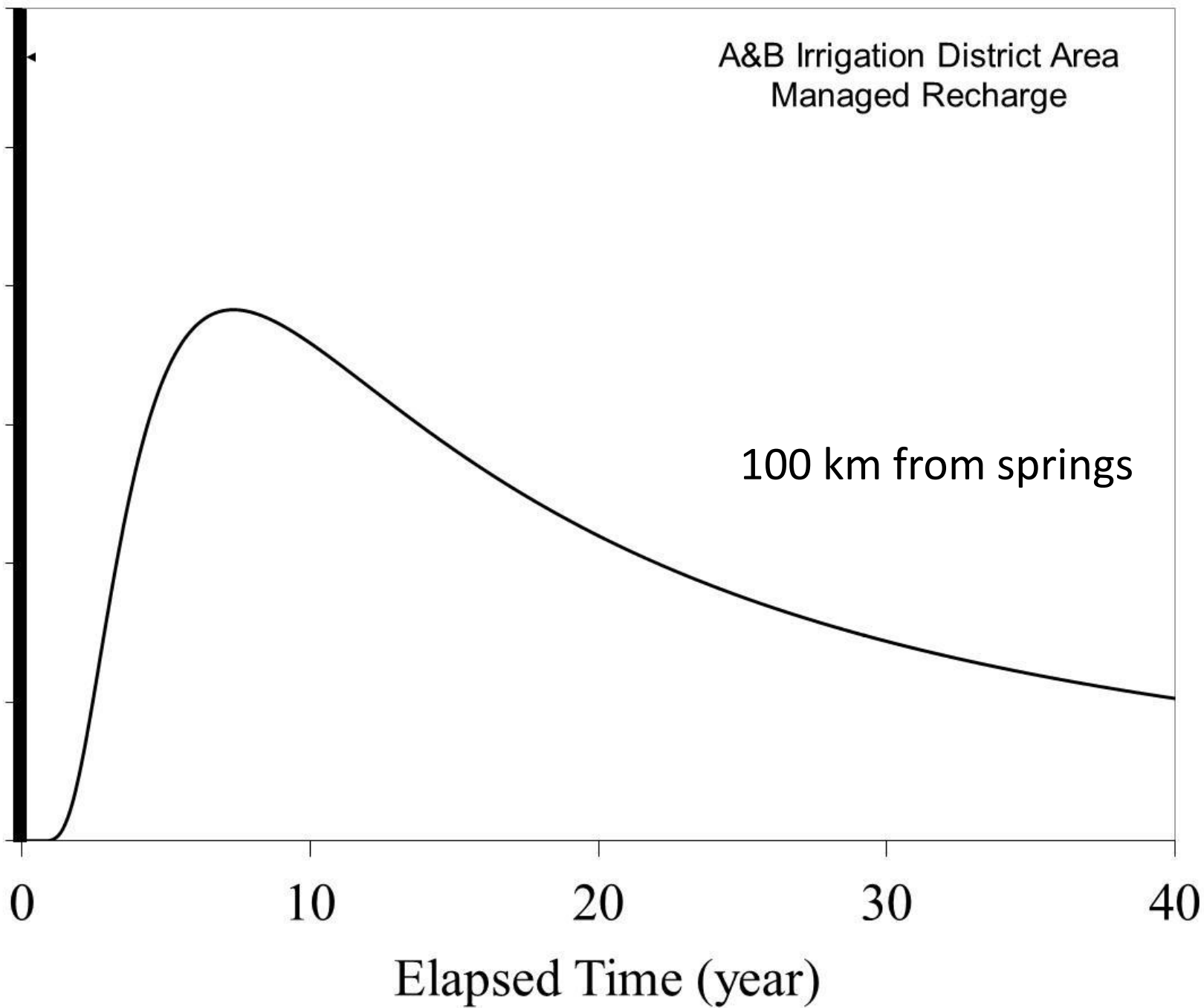
# Instantaneous Recharge

- $\text{Lag} = t_{\max} = \frac{r^2}{6D}$
- $\text{Attenuation} = Q_{\max} \approx 0.925 \frac{VD}{r^2}$

**Spring Discharge**

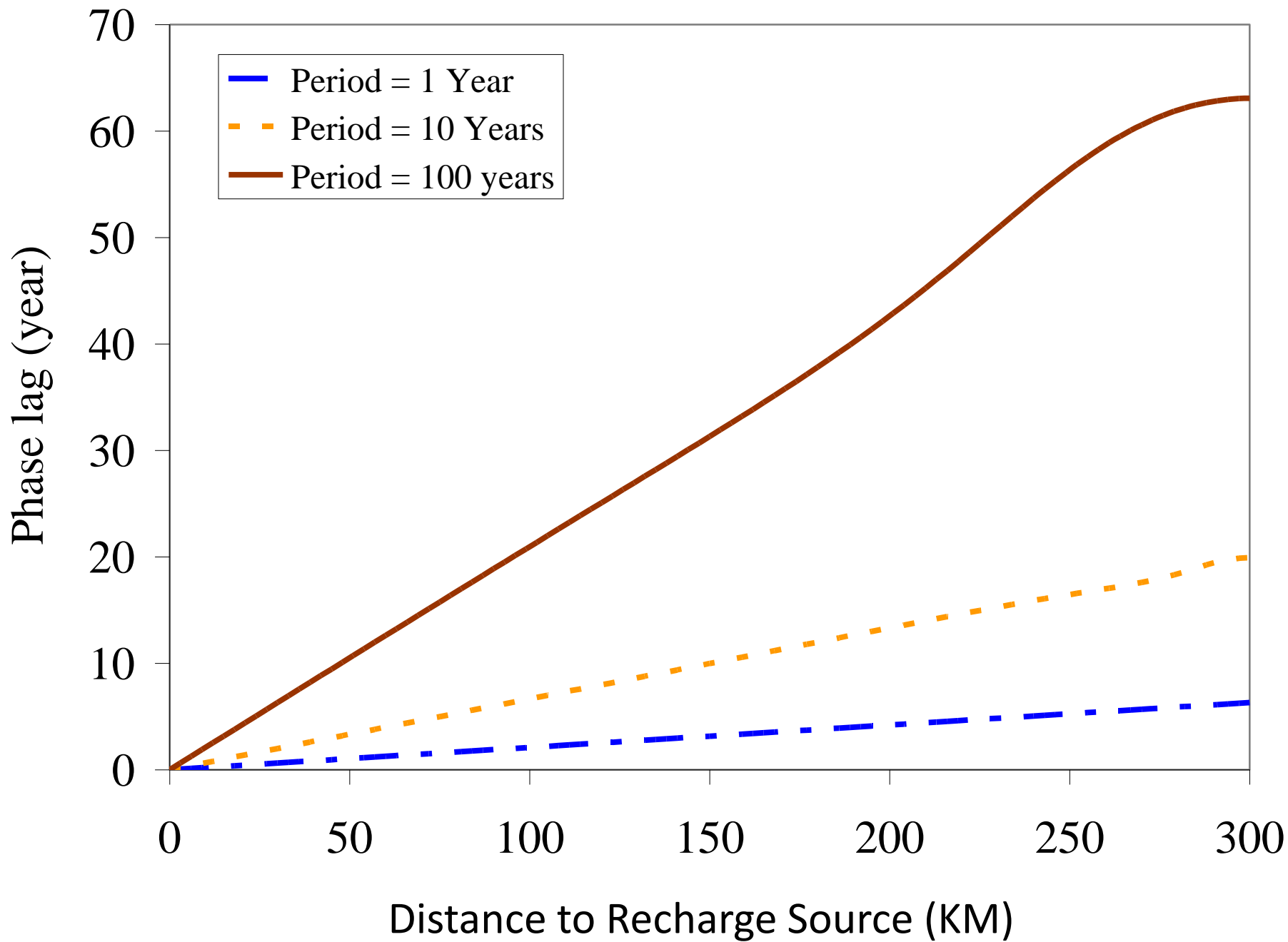


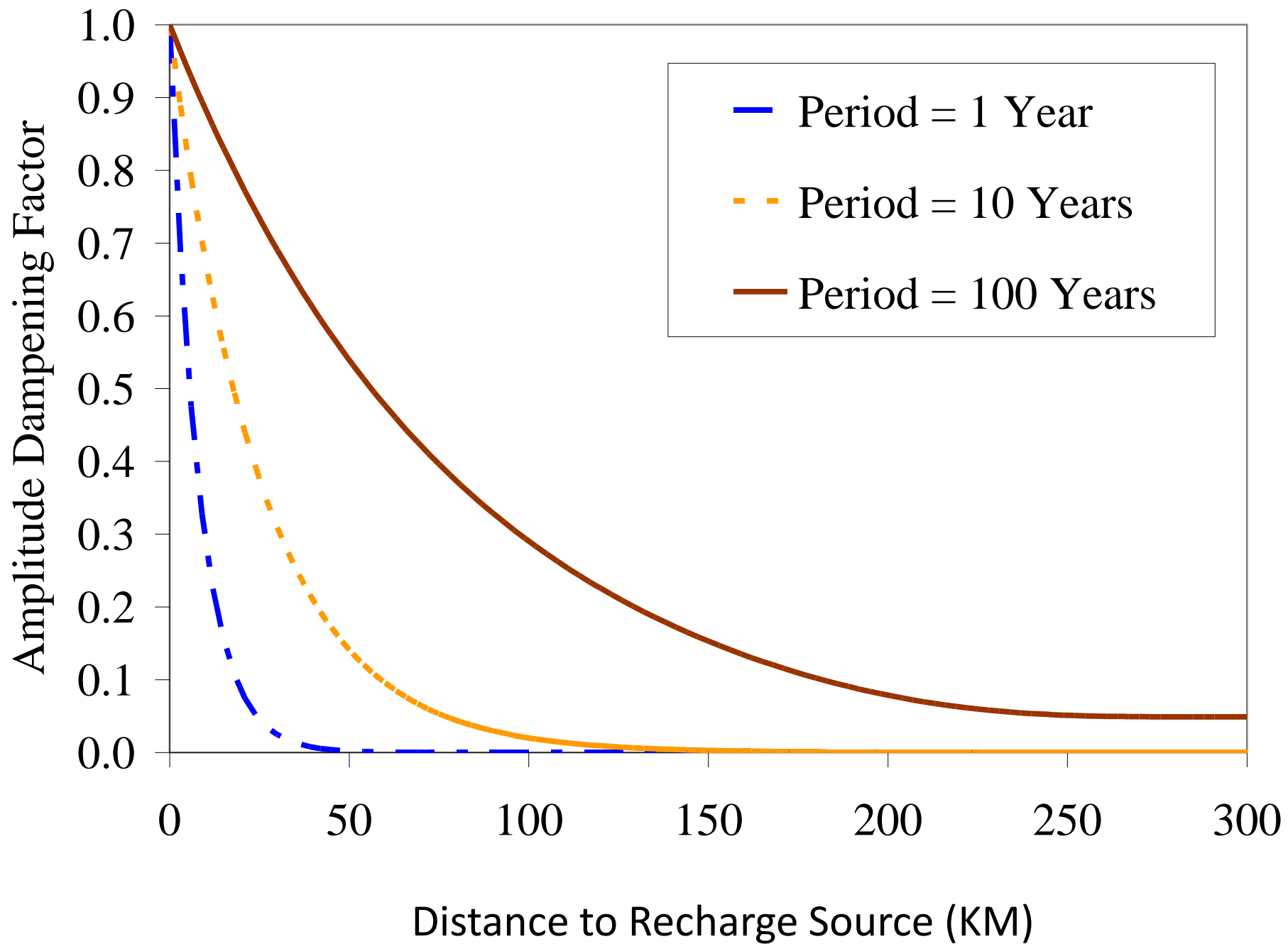
**Spring Discharge**



# Periodic Recharge

- Phase shift (lag) =  $\frac{r}{2\pi} \sqrt{\frac{\omega}{2D}}$
- Attenuation (ratio of discharge amplitude to recharge amplitude) =  $\exp\left(-r \sqrt{\frac{\omega}{2D}}\right)$





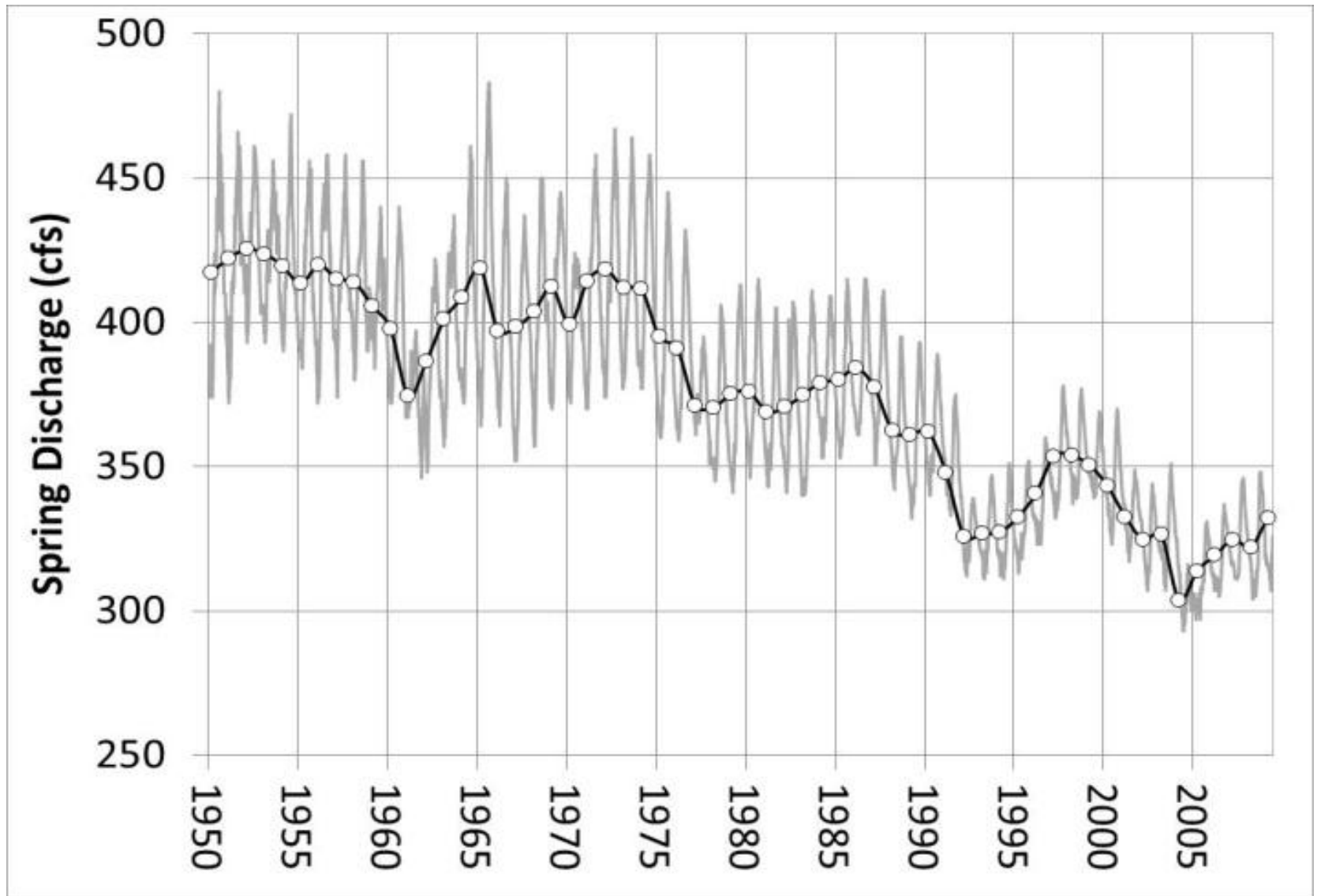
# Analytical Approach Conclusions

- Relationship between lag, attenuation and distance (aquifer time scale control)
- Short-term changes in aquifer stresses near the discharge location account for most of the annual and decadal-scale aquifer discharge variability

Are the relationships among lag time, attenuation, and distance between aquifer stresses and aquifer discharge evident in measured data?

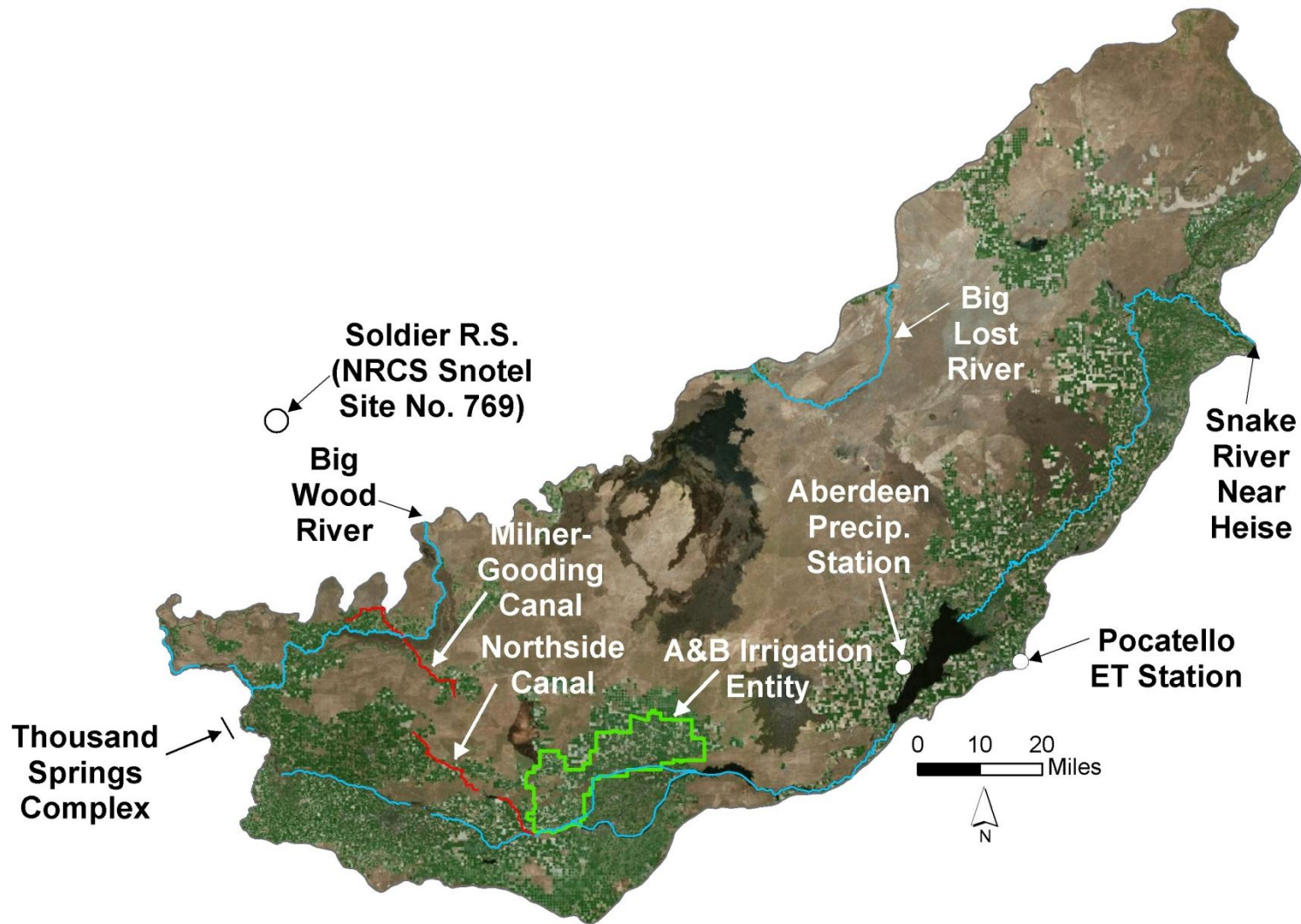
# Chapter 2. Statistical Approach

# Response Variable



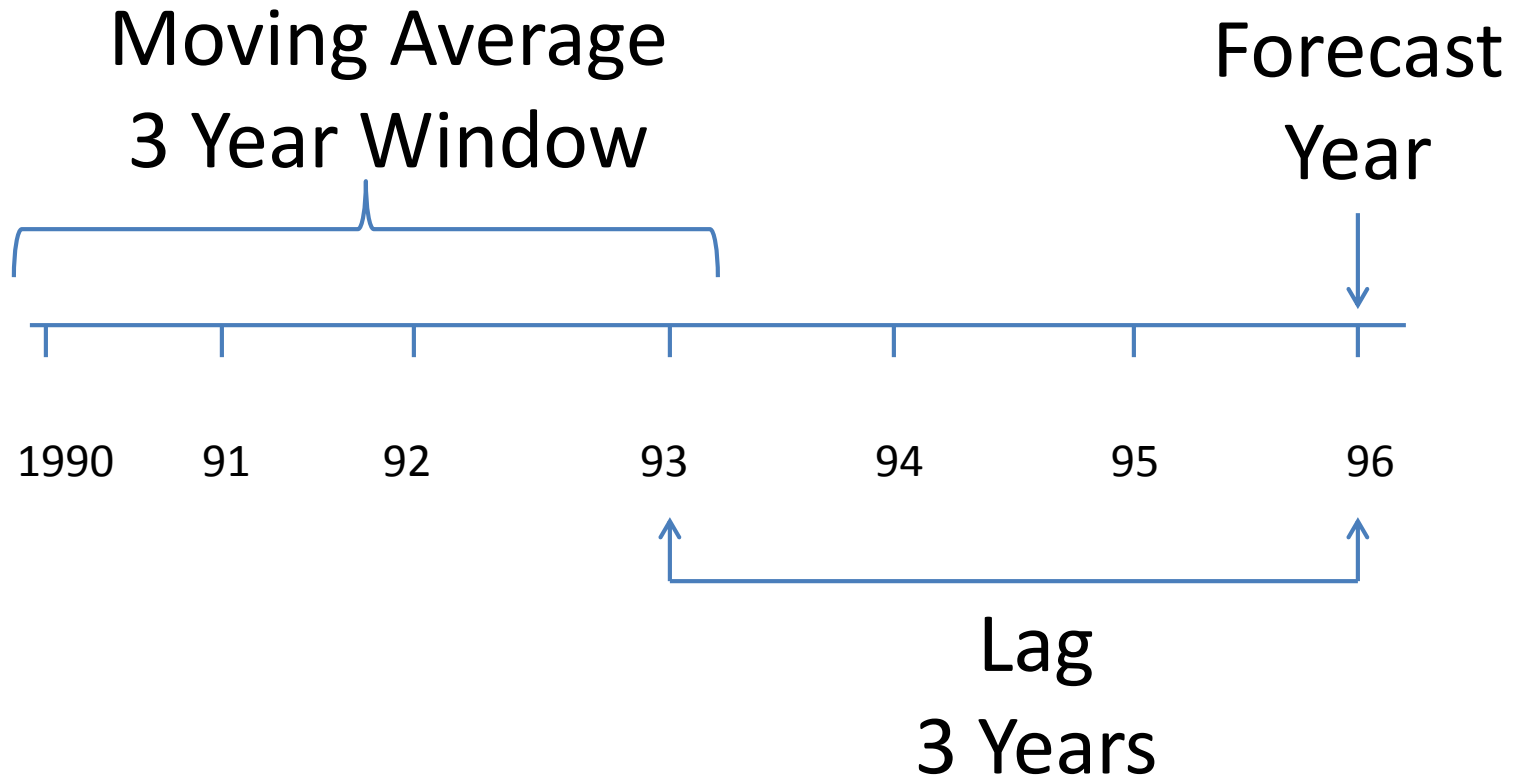
# Predictor Variables

Variable
BLRiver
BWDiv
BWRiver
ET
MGDiv
NSDiv
Precip
Pump
Sprinkler
Stor
SWE

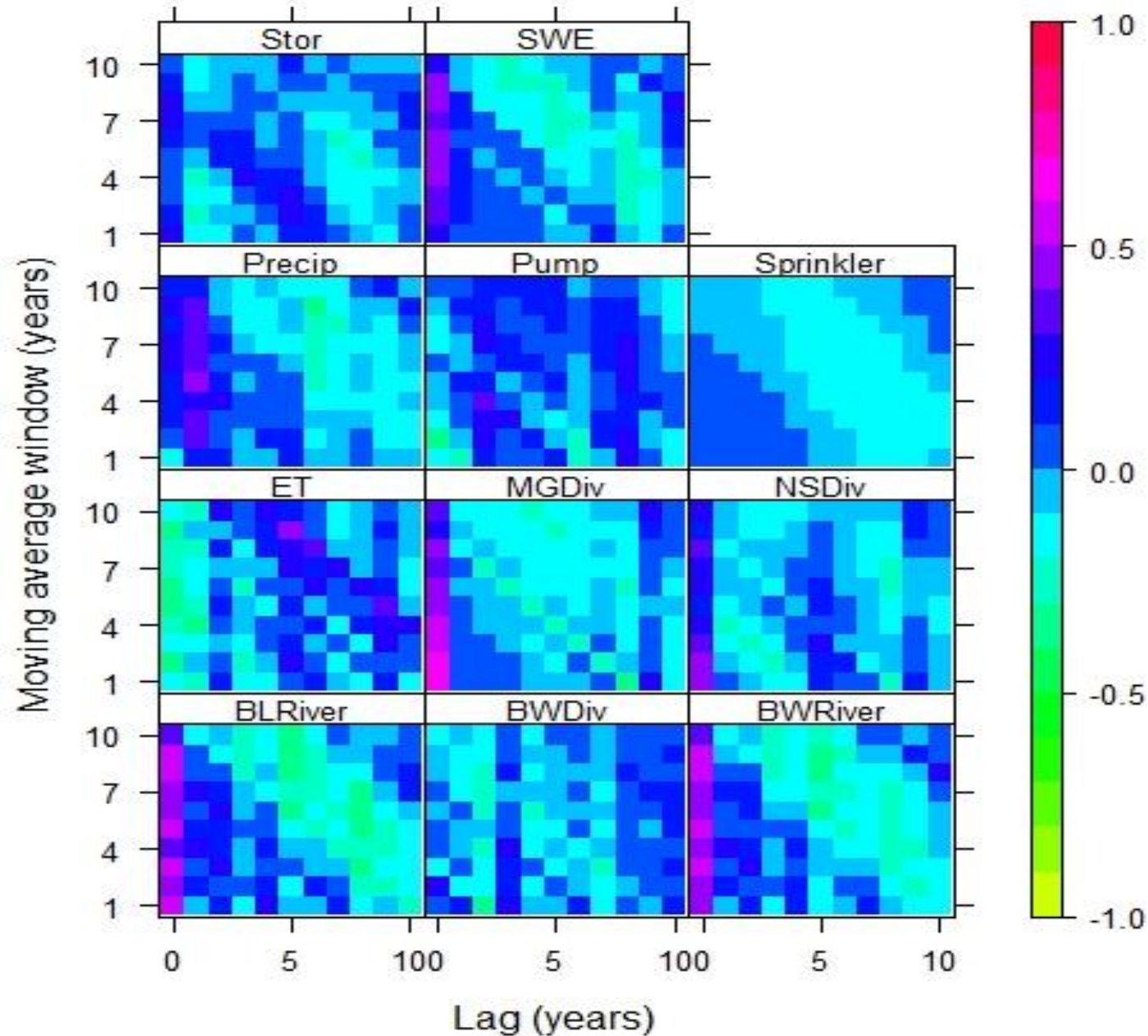


# Statistical Methods

Predictors potentially lagged in time and averaged over several years



# Optimum Lag and MAW



# ARIMAX model

$$y(t) - y(t - 1) = \sum_{k=1}^p \beta_k (x_k(t) - x_k(t - 1)) + \varepsilon_t$$

- Spring Q is a combination of last year's spring Q plus a combination of exogenous predictors at an optimum Lag and MAW for each predictor

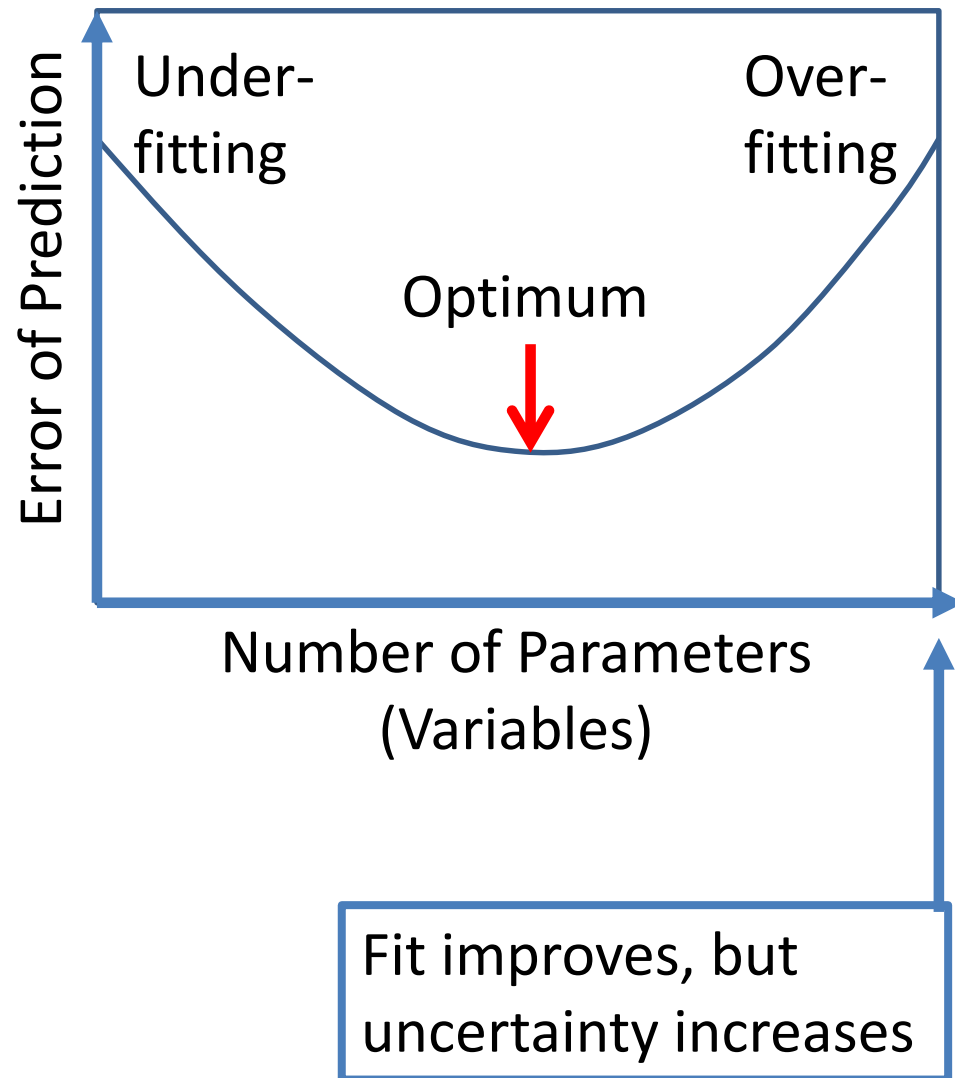
# Statistical Methods

- Divided data into two sets:
  1. Calibration (1950 through 1999)
  2. Validation (2000 through 2010)
- Akaike's information criterion ( $AIC_c$ )

$$AIC_c = n[\log(\sigma^2) + 1 + \log(2\pi)] + 2K + \frac{2K(K+1)}{n-K-1}$$

# Model-Based Inference

- Model Selection
- Multiple Working Hypotheses
- Strength of Evidence



# Candidate Models

	Predictor(s)							
Model	BWRiver	ET	MGDiv	NSDiv	Precip	Pump	Stor	SWE
A	•	•	•	•	•	•	•	•
B	No predictors (null model, random walk)							
C	Temporal trend only (random walk with drift)							
D	•	•	•	•	•	•	•	
E	•		•	•	•	•	•	•
F	•	•	•	•	•	•		•
G	•	•	•	•	•		•	•
H	•	•	•	•		•	•	•
I	•		•	•				
J	•			•				
K	•		•					
L			•	•				
M	•		•	•				•
N	•	•	•	•				
O	•		•	•			•	
P	•		•	•		•		
Q	•		•	•	•			
R	•		•	•			•	•
S	•	•	•	•			•	•
T	•		•	•		•	•	•
U	•		•	•	•		•	•

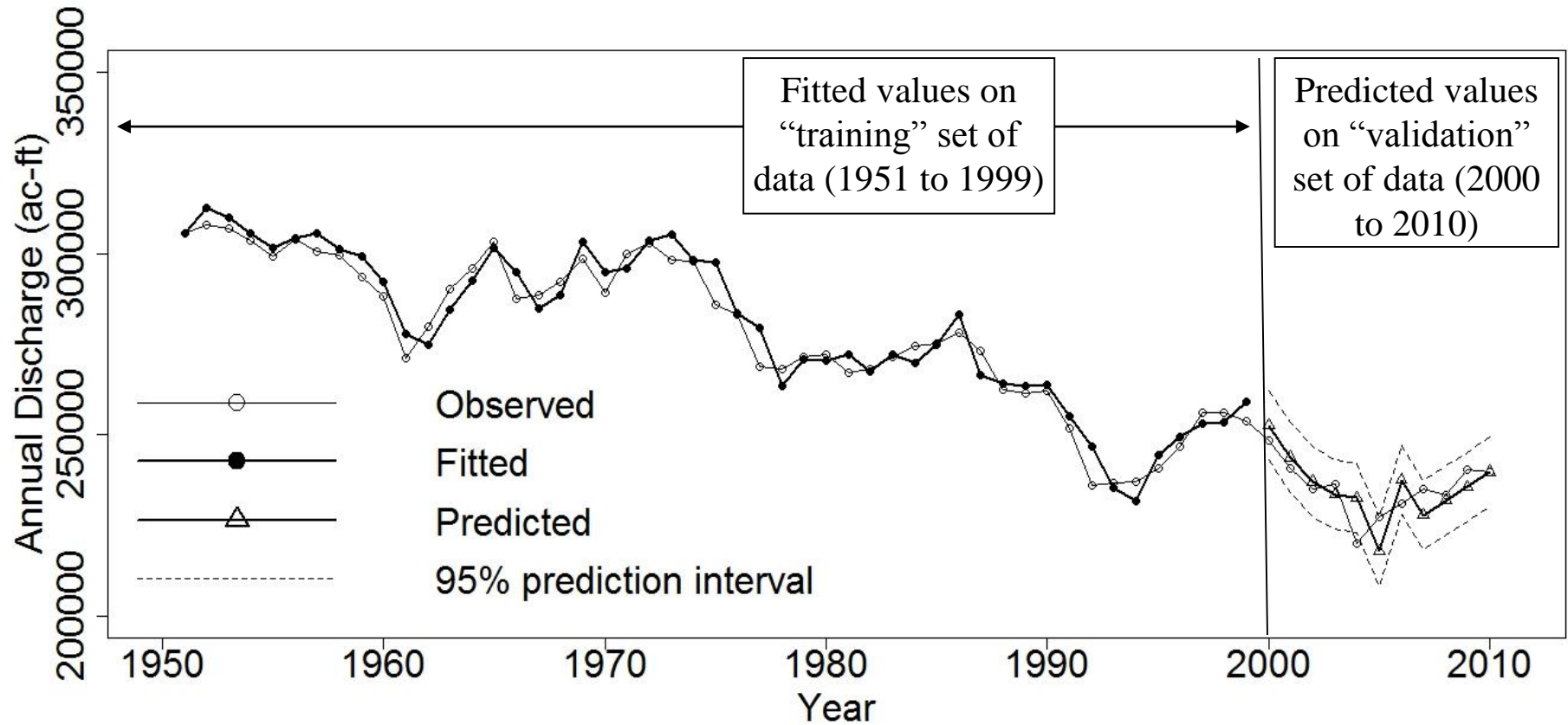
# Model 1 Approach

- Use only historic data to forecast Spring Q  
(data available each April)

# Comparing Models (AICc)

Model & Predictors	AICc	$\Delta AICc$	$w_i$	$\sum w_i$
U: BWRiver,MGDiv,NSDiv,Precip,Stor,SWE	985.9	0.00	0.34	0.34
E: BWRiver,MGDiv,NSDiv,Precip,Pump,Stor,SWE	986.2	0.36	0.28	0.62
F: BWRiver,ET,MGDiv,NSDiv,Precip,Pump,SWE	988.1	2.26	0.11	0.73
A: BWRiver,ET,MGDiv,NSDiv,Precip,Pump,Stor,SWE	988.2	2.36	0.10	0.83
G: BWRiver,ET,MGDiv,NSDiv,Precip,Stor,SWE	988.3	2.42	0.10	0.94

# Model 1

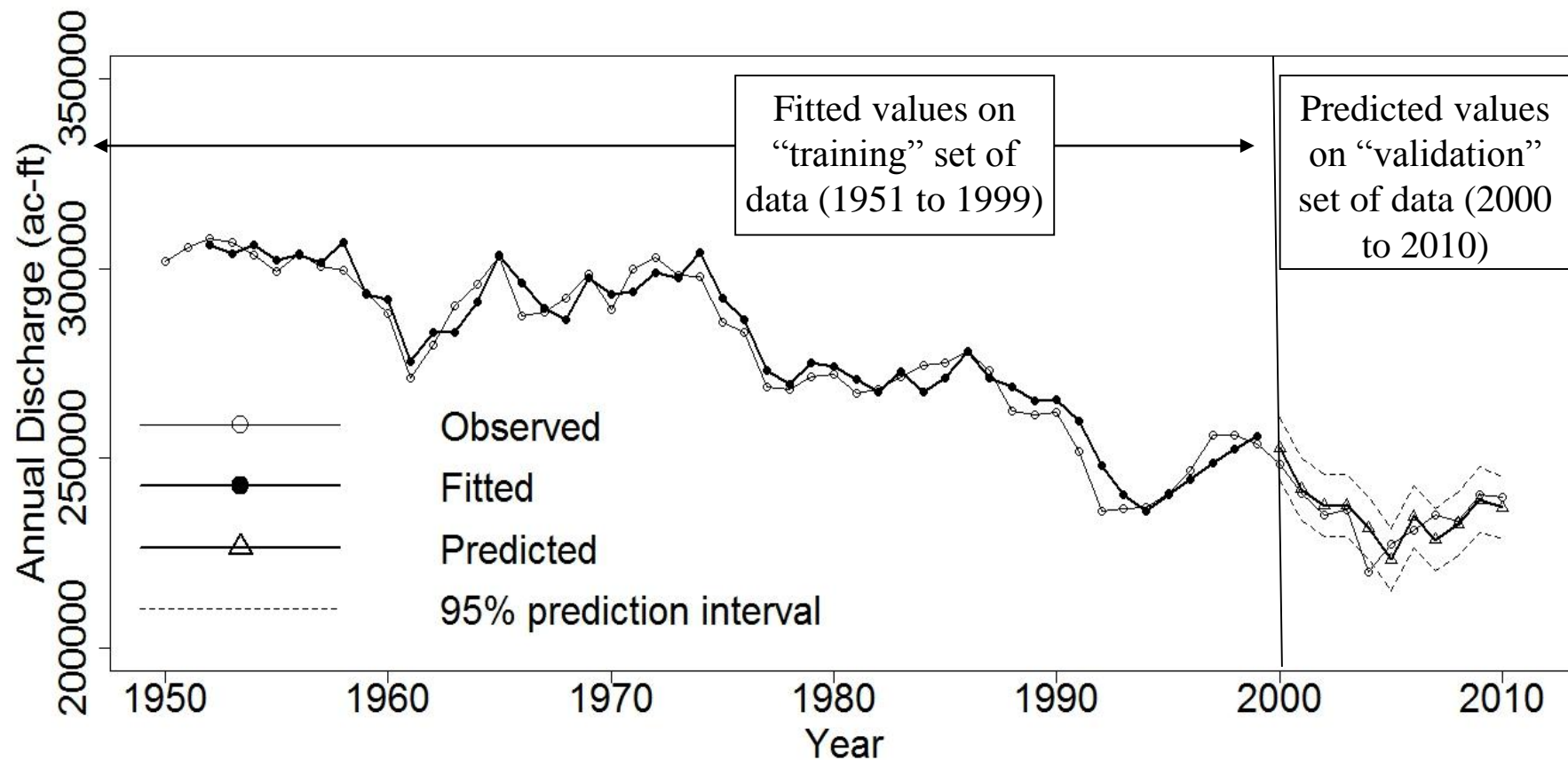


# Model 2

- Recharge sources impact spring discharge in the same year the recharge occurs
  - Inclusion of diversion, streamflow, pumping, and ET variables for the upcoming water year

# Top Models (AICc)

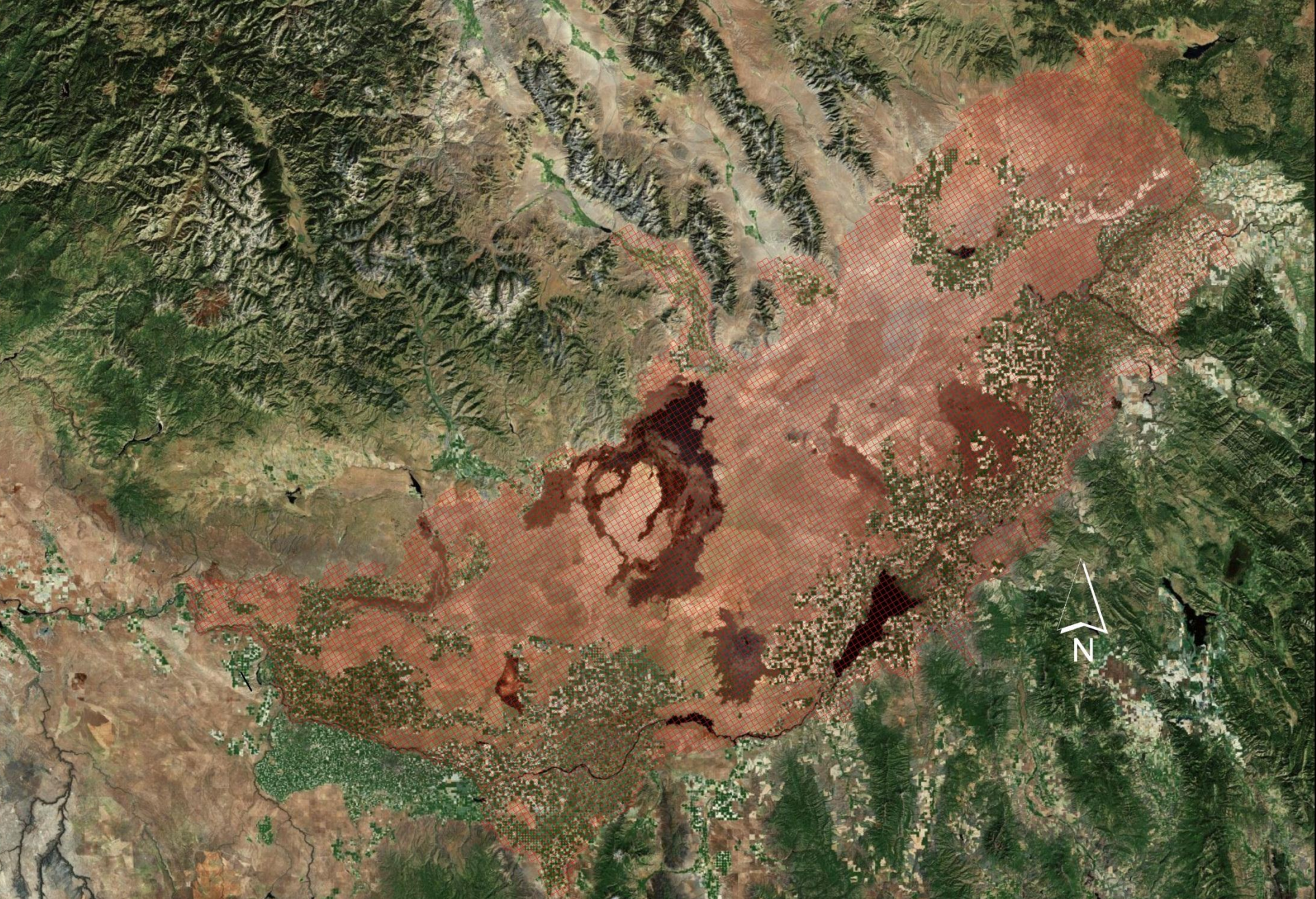
Model & Predictors	AICc	$\Delta AICc$	$w_i$	$\sum w_i$
O: BWRiver,MGDiv,NSDiv,Stor	970.1	0.00	0.37	0.37
S: BWRiver,MGDiv,NSDiv,ET,Stor,SWE	972.3	2.20	0.12	0.49
R: BWRiver,MGDiv,NSDiv,Stor,SWE	972.5	2.46	0.11	0.60
D: BWRiver,MGDiv,NSDiv,ET,Precip,Pump,Stor	973.0	2.98	0.08	0.69
T: BWRiver,MGDiv,NSDiv,Pump,Stor,SWE	973.1	3.07	0.08	0.77
H: BWRiver,MGDiv,NSDiv,ET,Pump,Stor,SWE	973.5	3.43	0.07	0.83



# Conclusions

1. Model 2 explained nearly twice as much variability in discharge
  - Analytical results (lag, attenuation, distance) are observed in recharge-discharge data (stresses close come out in the same year)
2. The model with the highest AIC weight included streamflow, two irrigation diversion variables, and “second tier” variables (Stor, SWE).
3.  $AIC_c$  model ranking is an effective way to evaluate the relative strength of predictors

# Chapter 3. Numerical Approach



# ESPAM 2.0

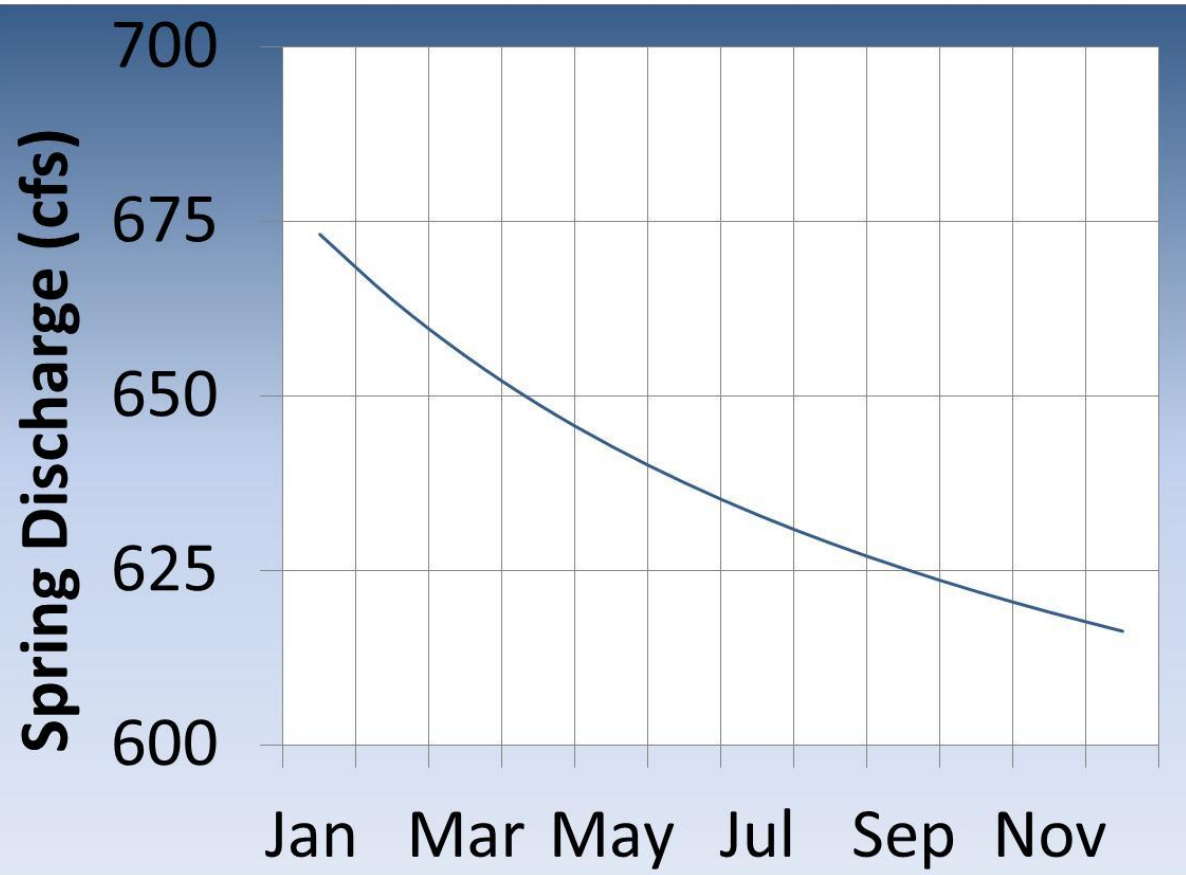
- Used to administer water rights (mitigation requirements, etc.)
- Single layer
- Monthly stress period
- Calibration period May 1980 through Oct. 2008
- MODFLOW 2000
- Superposition version

# Primary Spring Discharge Components

1. Decay of spring discharge from initial head conditions
2. Contributions to spring discharge from future recharge and pumping events

## Starting Heads

- 1 IDWR database
- 2 Interpolate head surf.
- 3 MODFLOW

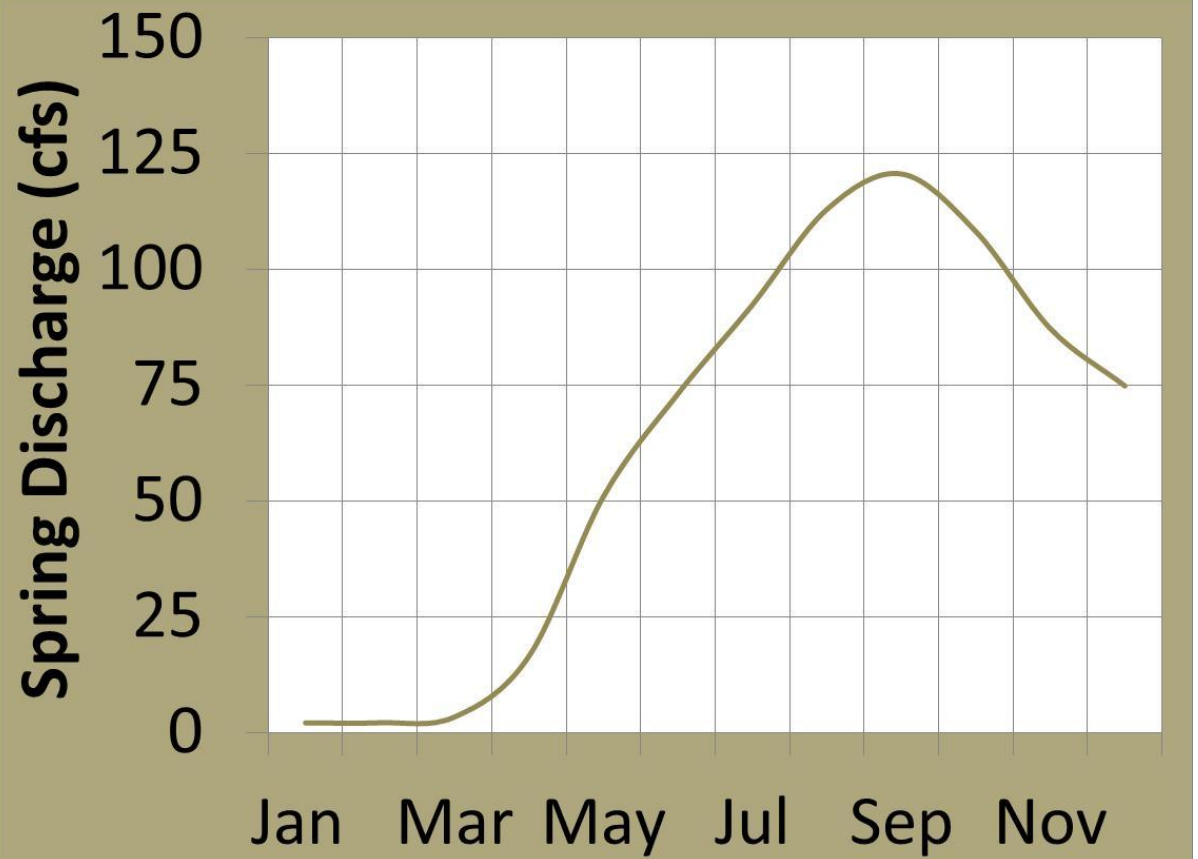


## Irrigation Recharge

1 Recharge  
Stress

2 MODFLOW

3 Response

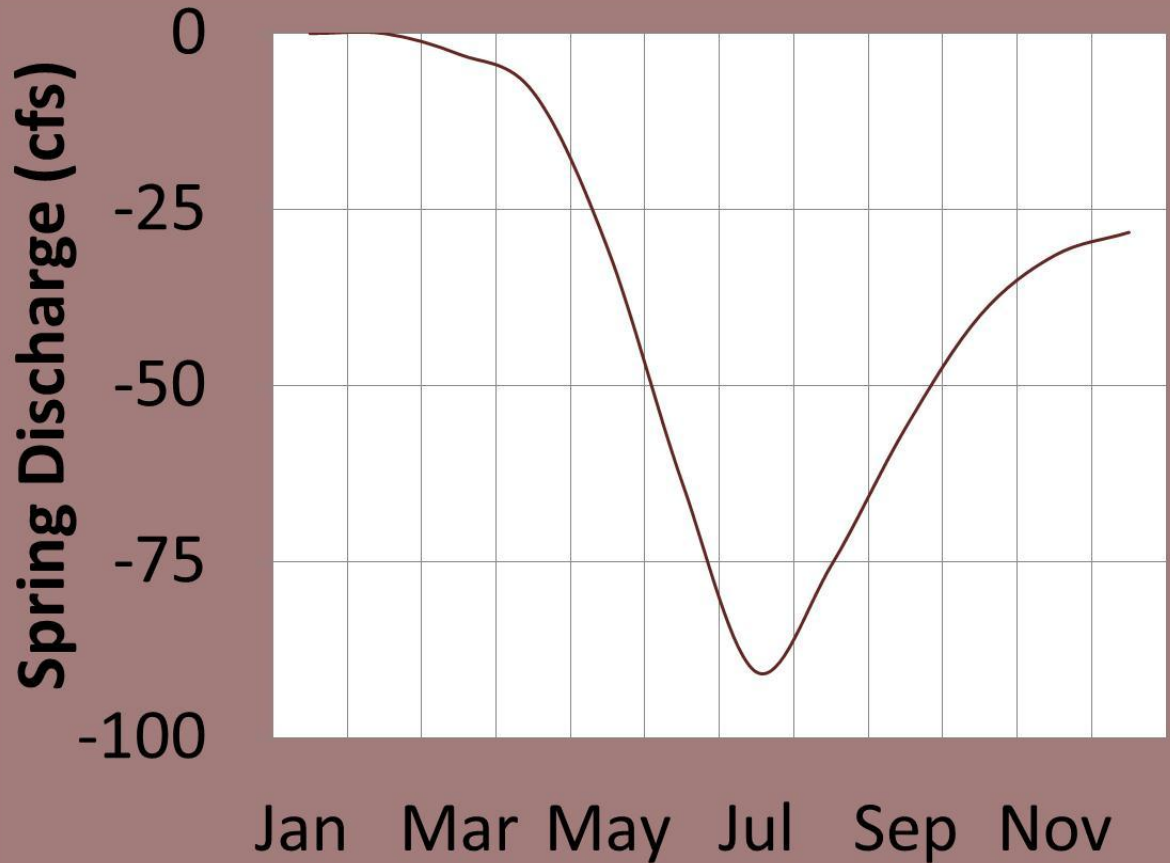


## Pumping

1 Average pumping

2 MODFLOW

3 Response



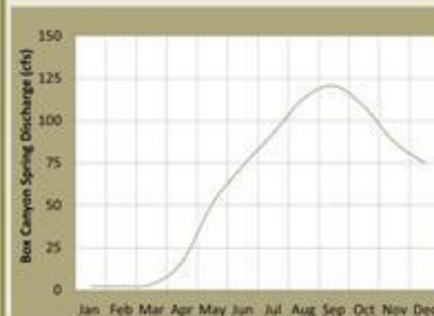
## Starting Heads

- 1 IDWR database
- 2 Interpolate head surf.
- 3 MODFLOW



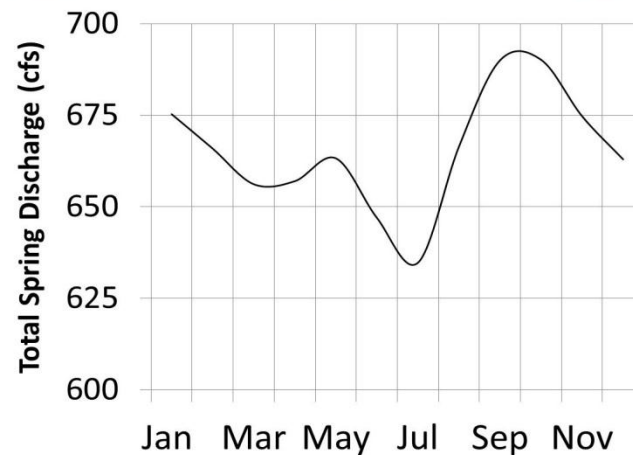
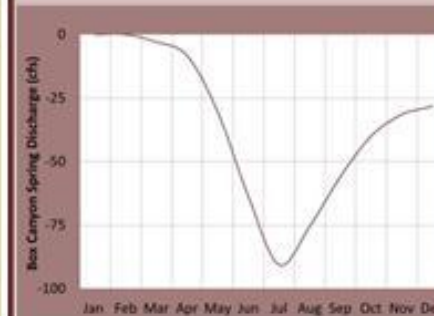
## Irrigation Recharge

- 1 Recharge Stress
- 2 MODFLOW
- 3 Response

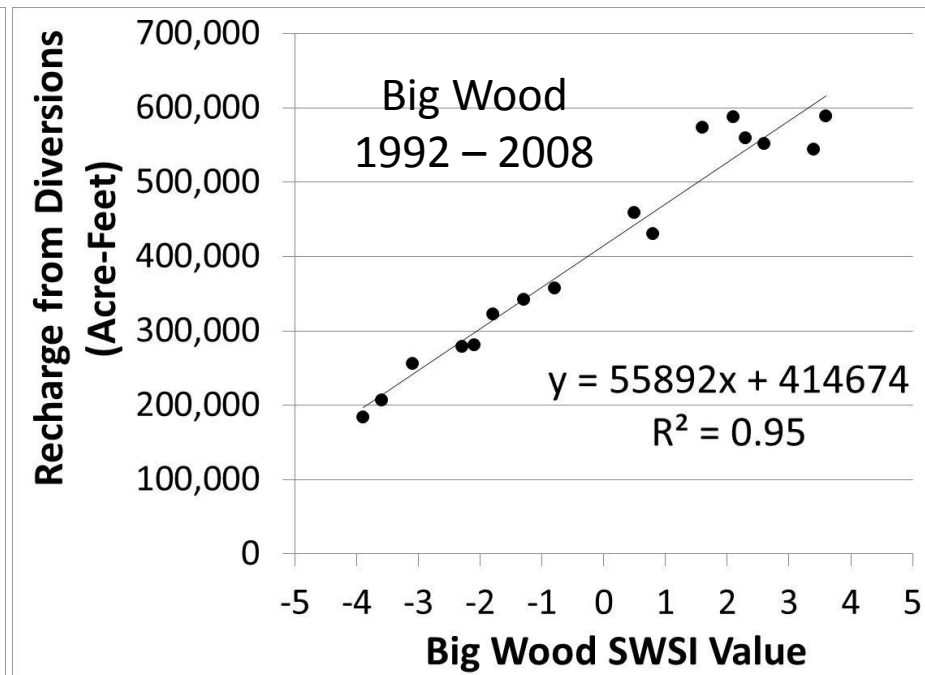
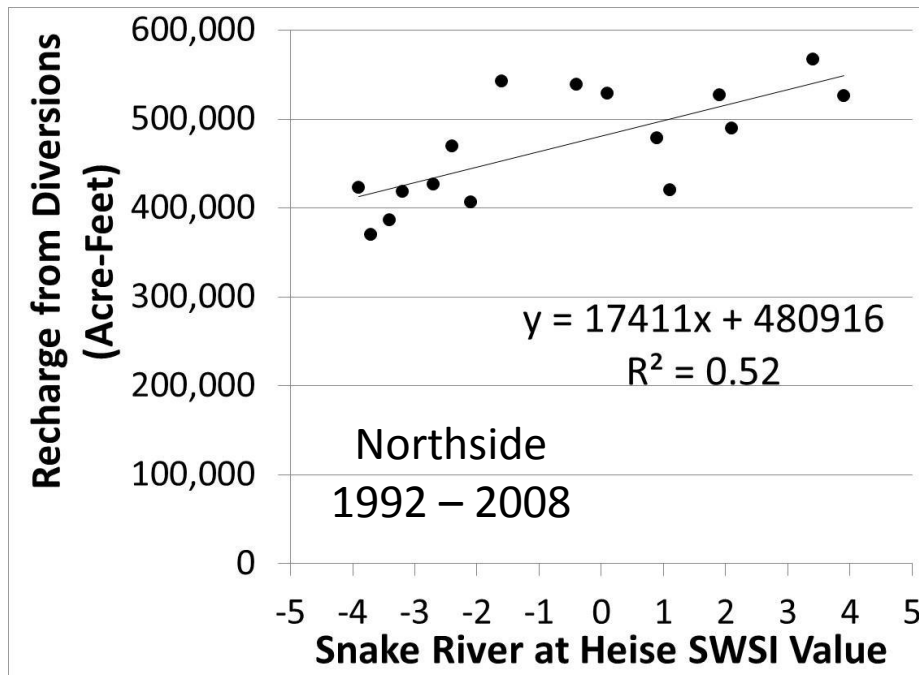


## Pumping

- 1 Average pumping
- 2 MODFLOW
- 3 Response

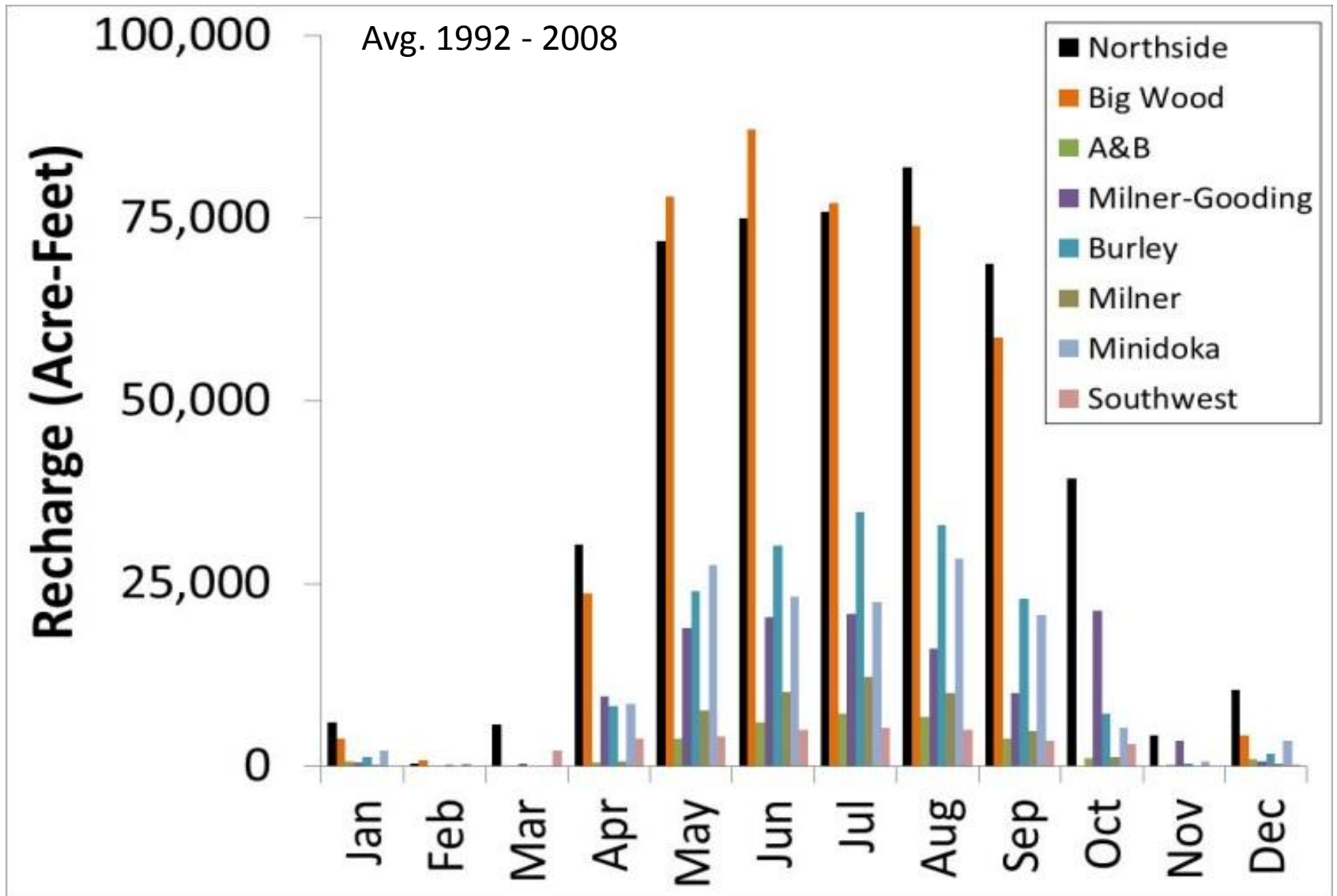


# SWSI and Irrigation Recharge



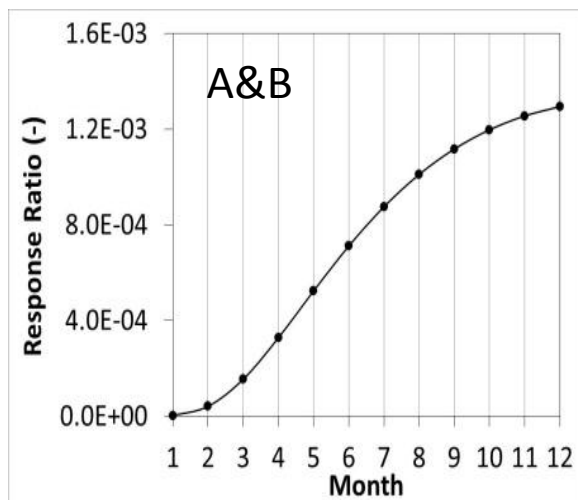
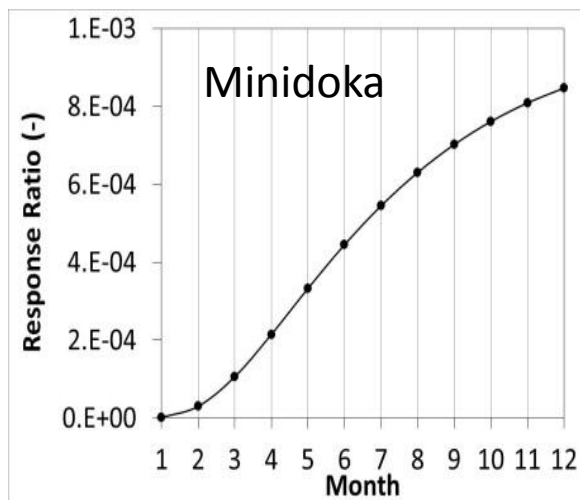
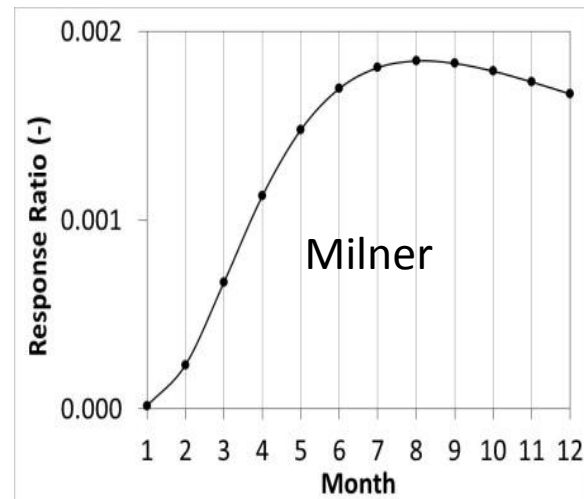
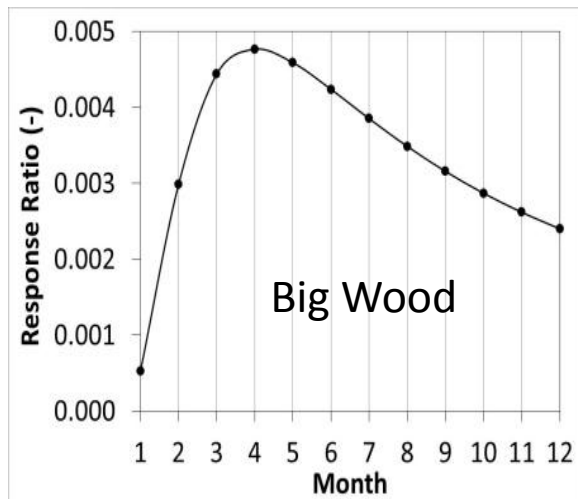
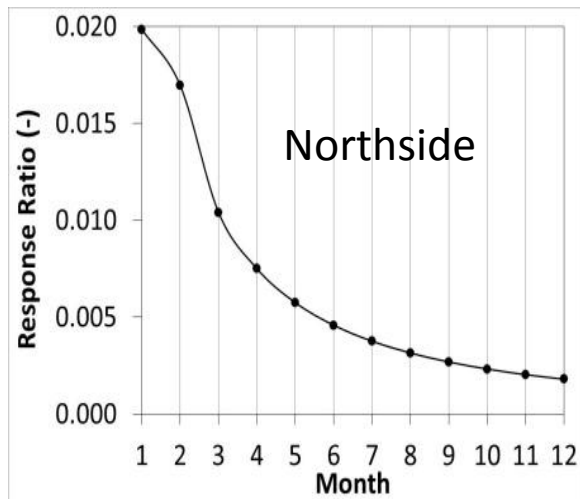
Source: NRCS (SWSI); IDWR MKMOD  
Summary (Calibration Run E120116A008)

# Irrigation Recharge

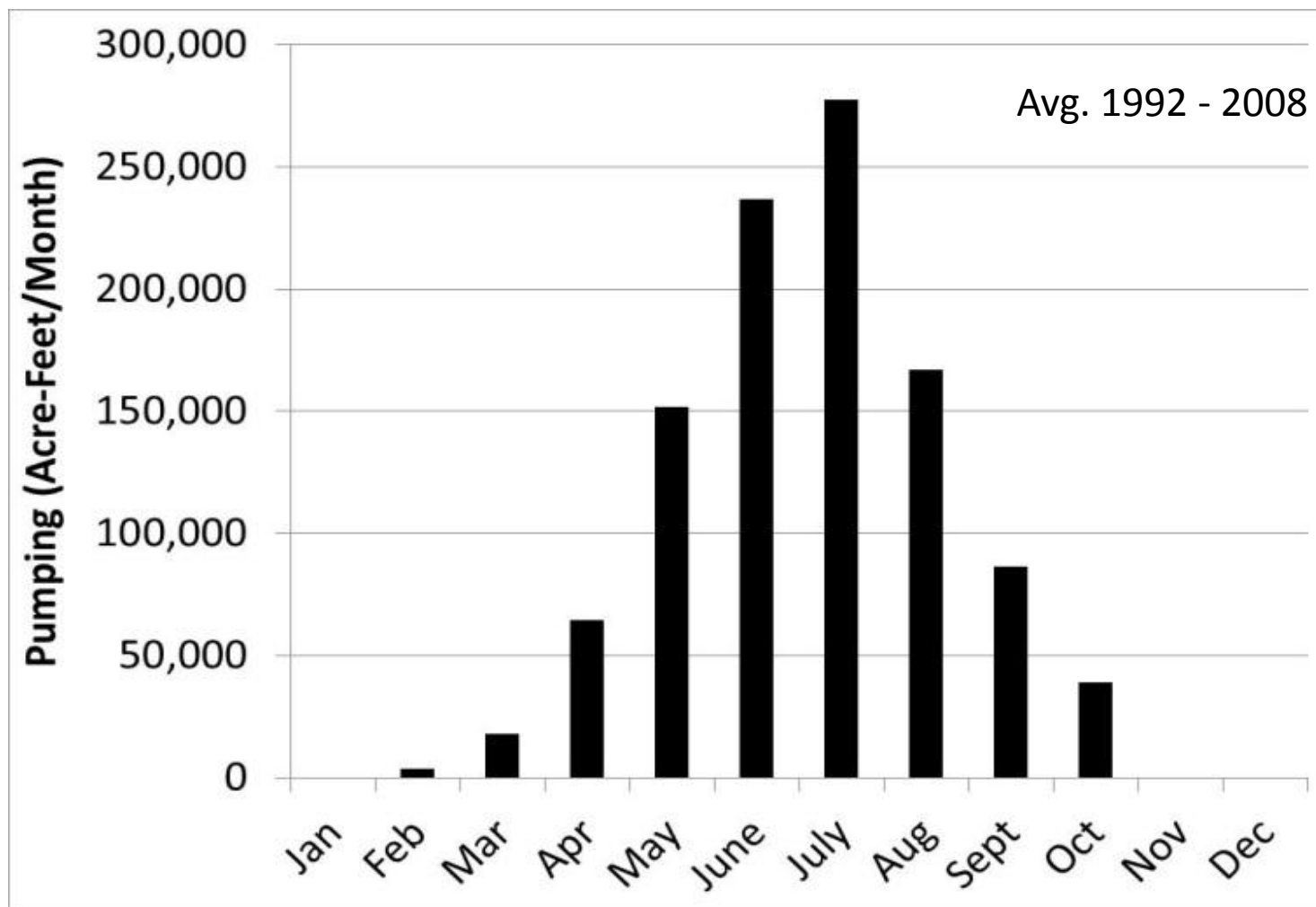


Source: IDWR MKMOD Summary (Calibration Run E120116A008)

# Irrigation Response Functions

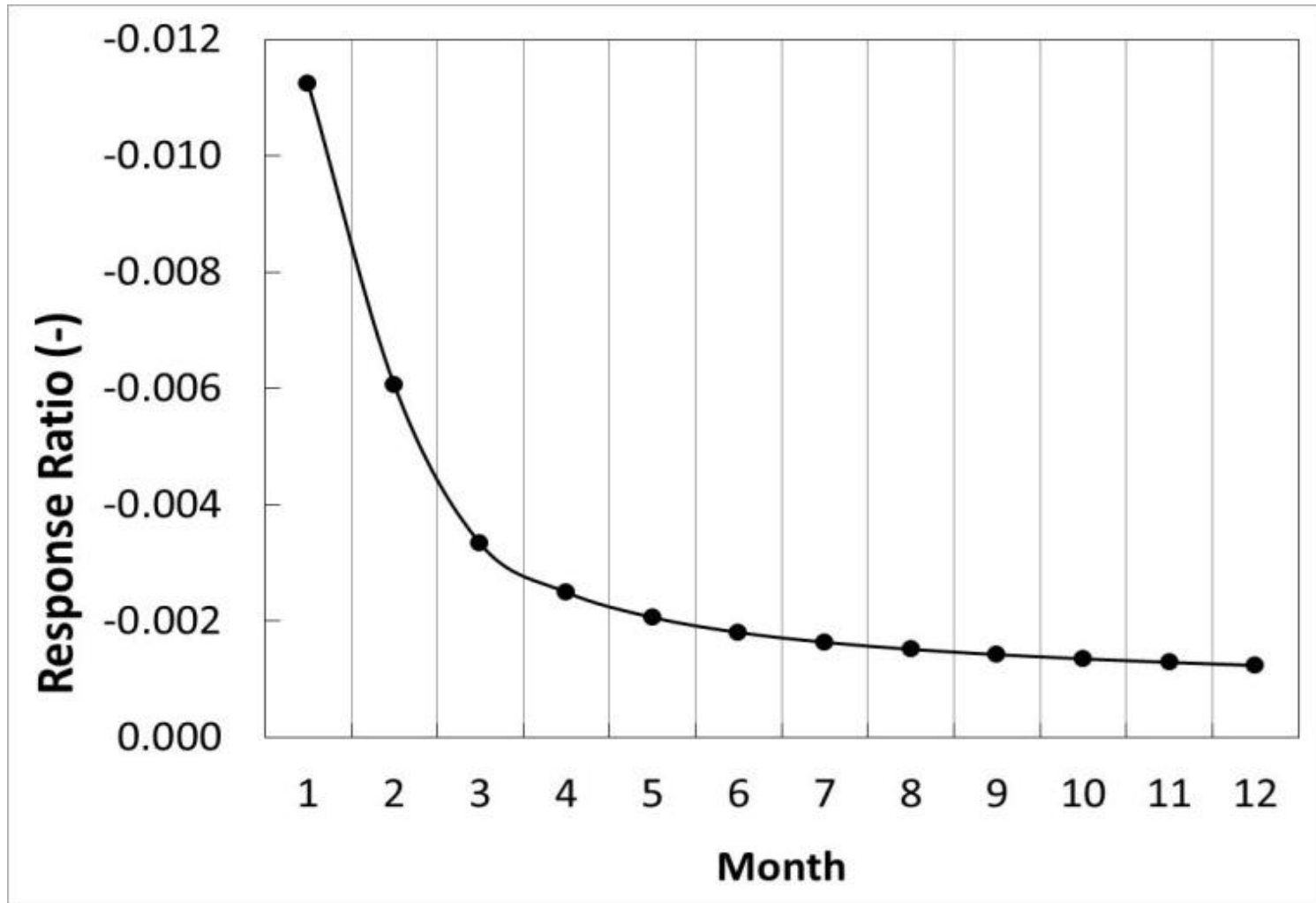


# Average ESPA Pumping

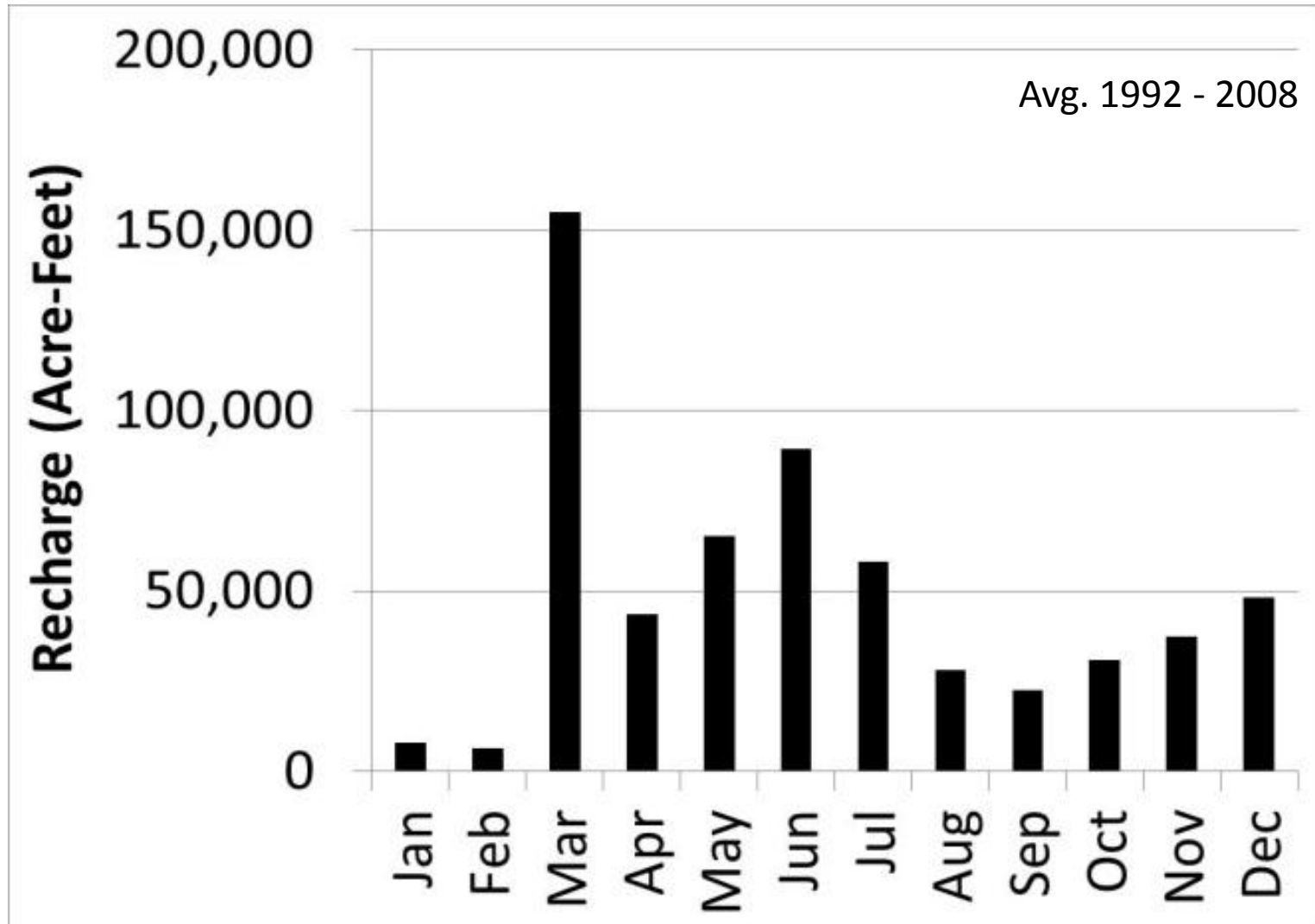


Source: IDWR MKMOD Summary (Calibration Run E120116A008)

# Pumping Response Function

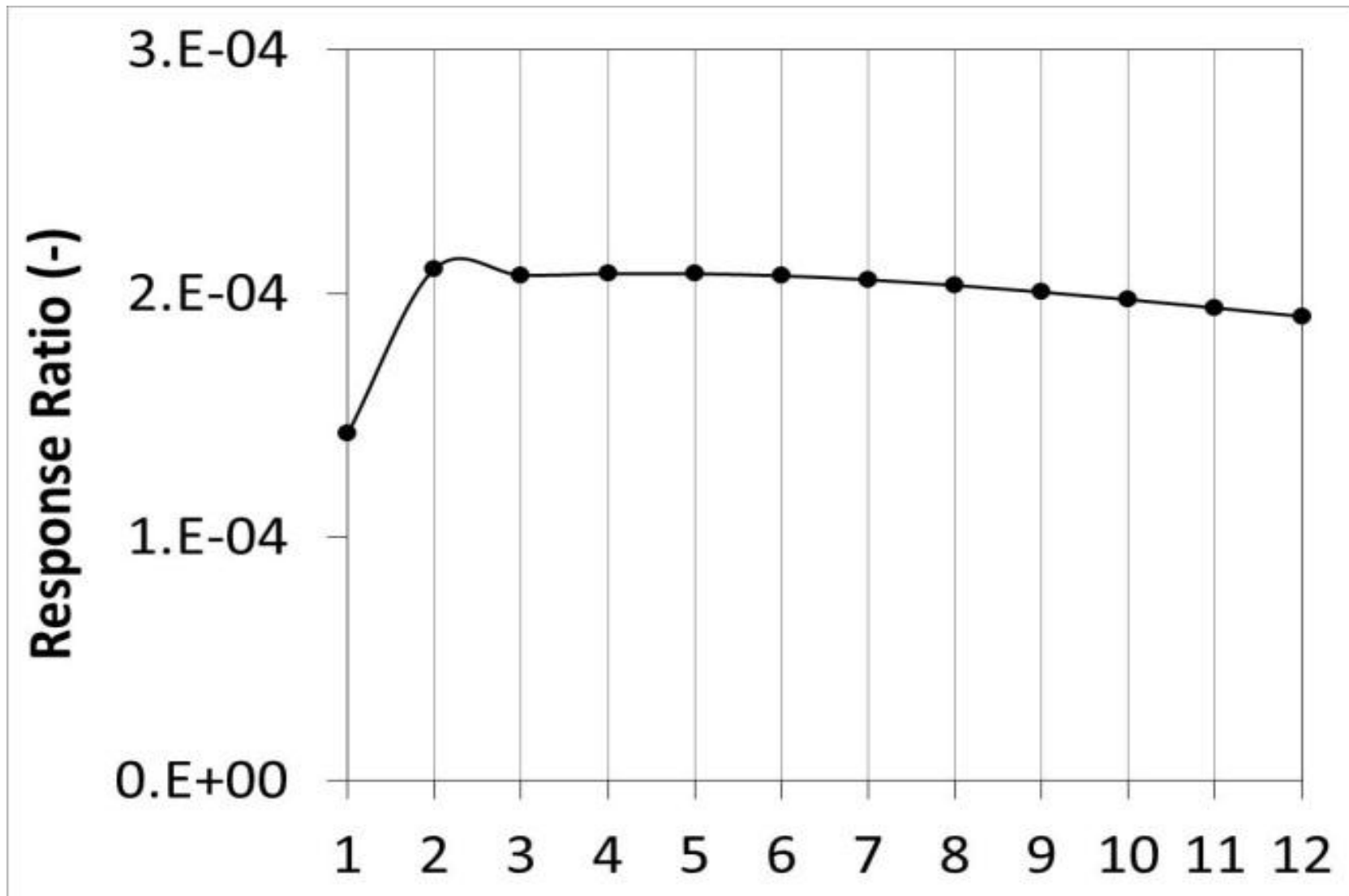


# Recharge on Non-Irrigated Lands



Source: IDWR MKMOD Summary (Calibration Run E120116A008)

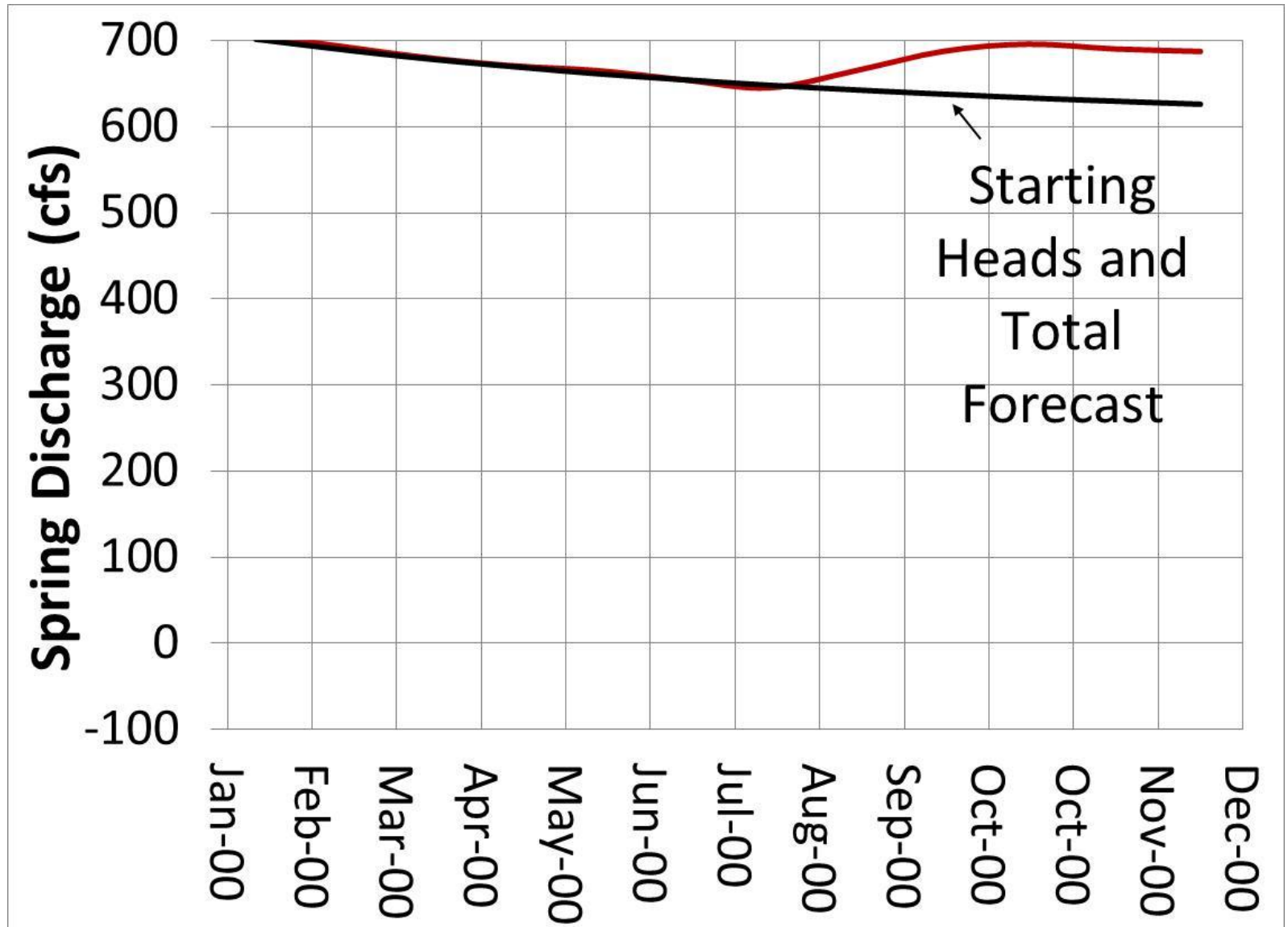
# NIR Response Function



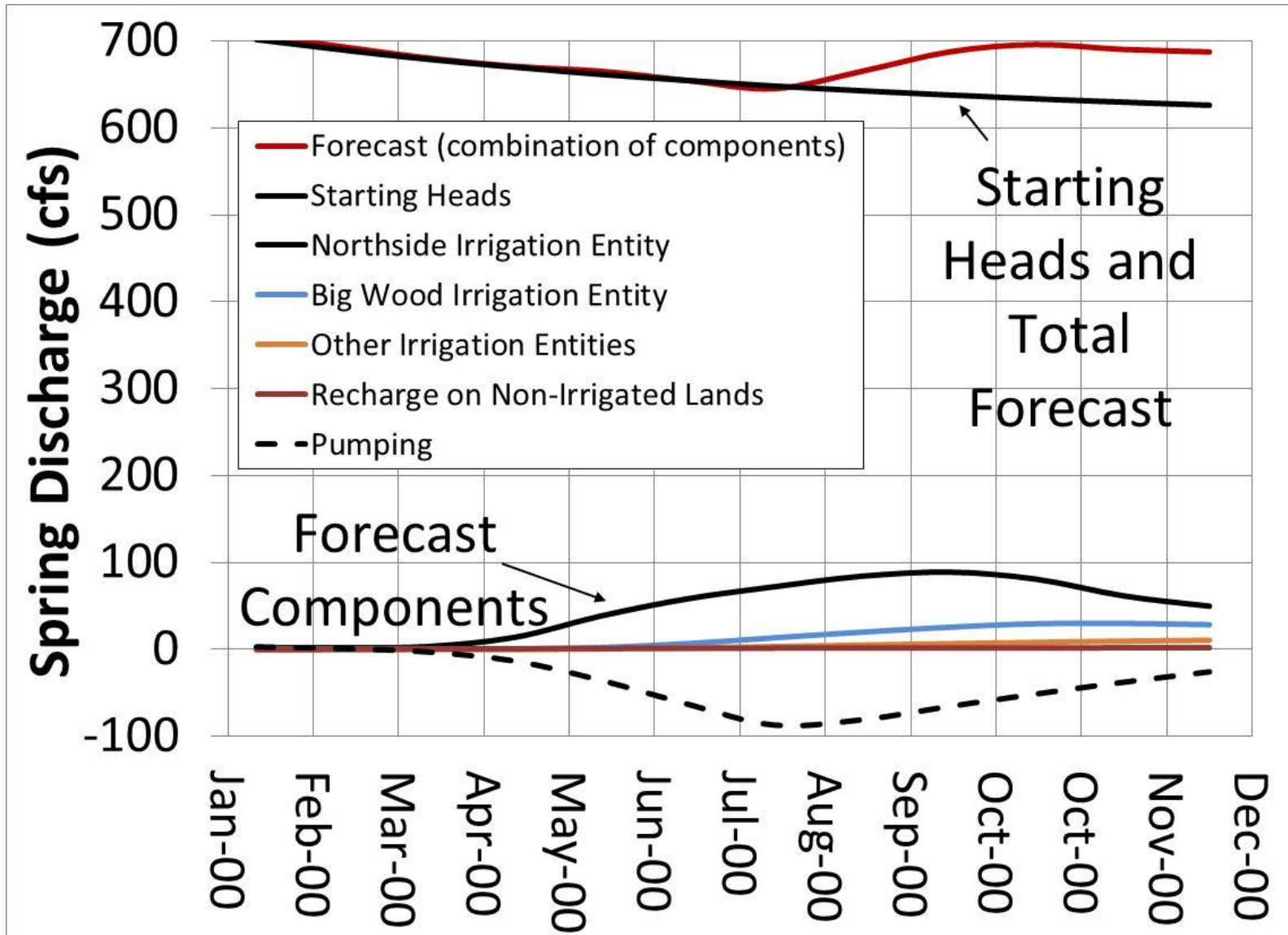
# Forecast Tool

- Spreadsheet (Excel – VBA coded)
- Combines the effects of starting heads and individual recharge components over time

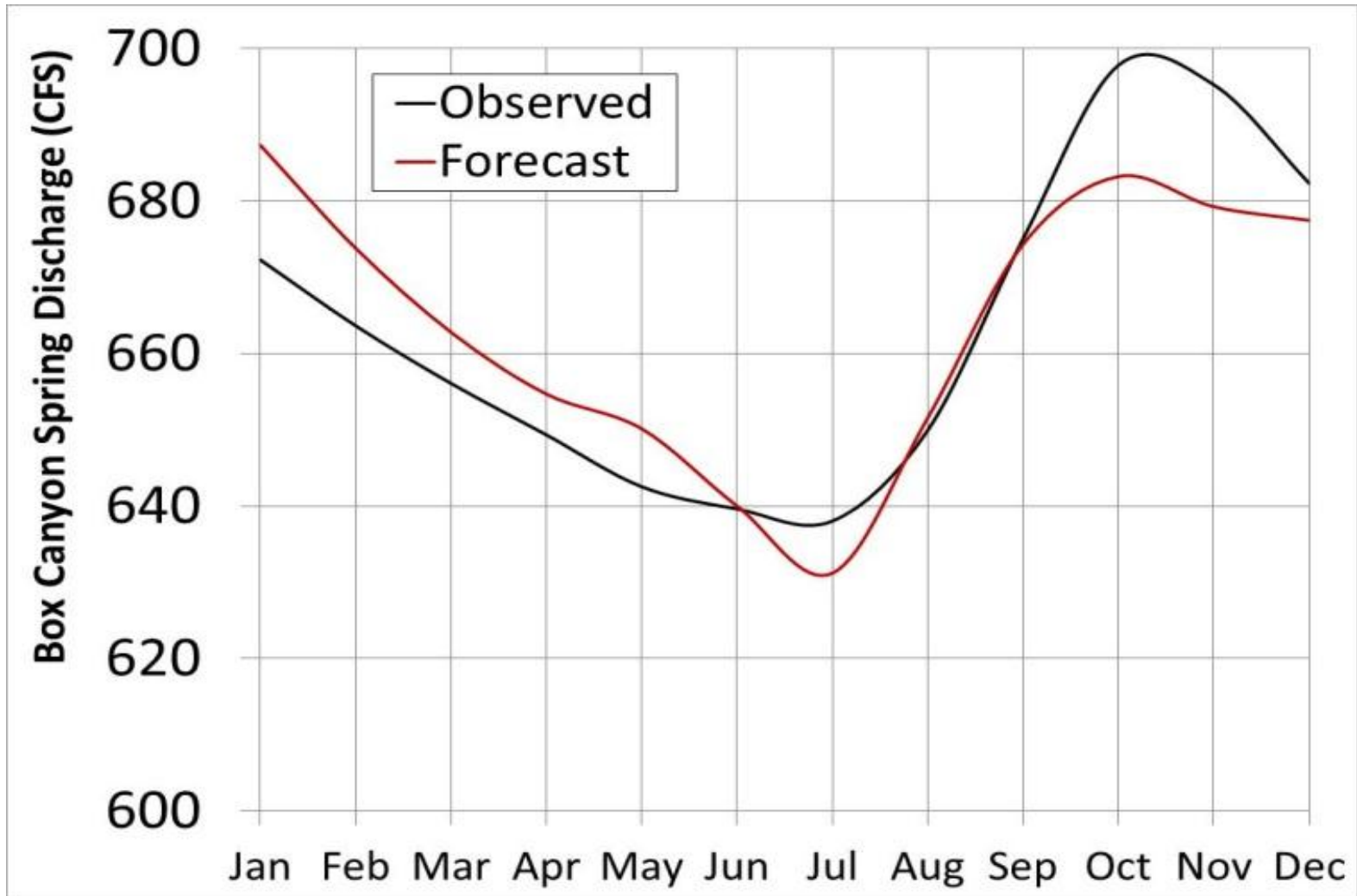
# Forecast Components



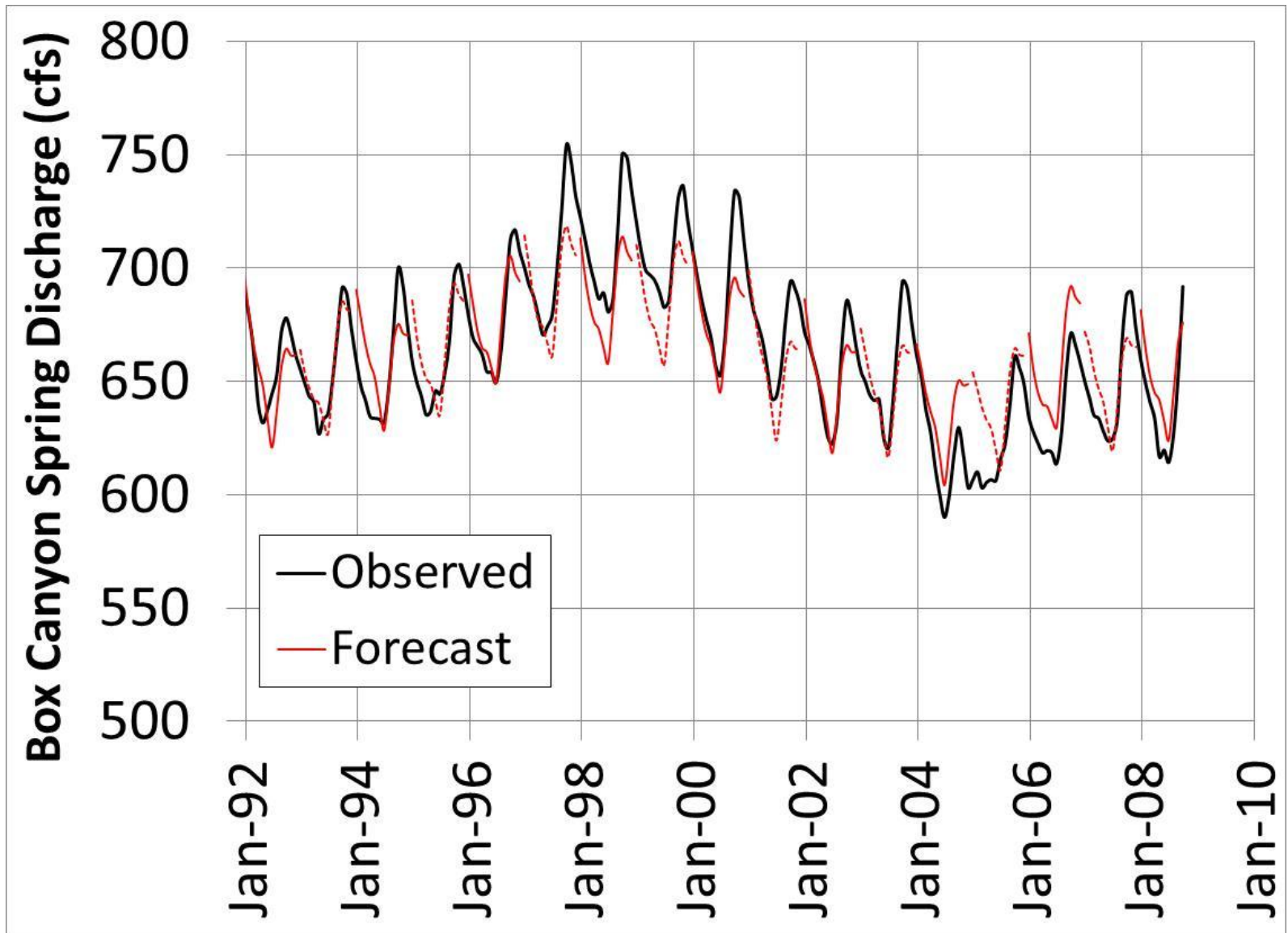
# Forecast Components



# Average Forecast



# Forecast Evaluation



# 2013 Forecast

## MONTHLY SPRING DISCHARGE FORECASTING TOOL

### USER INPUT

FORECAST YEAR

2013

January 1 Snake River at Heise SWSI

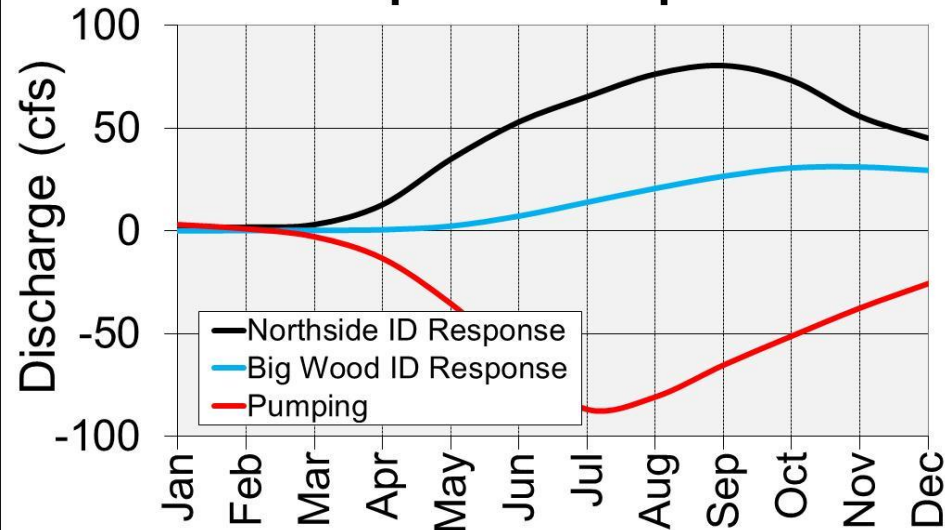
0.3

January 1 Big Wood SWSI

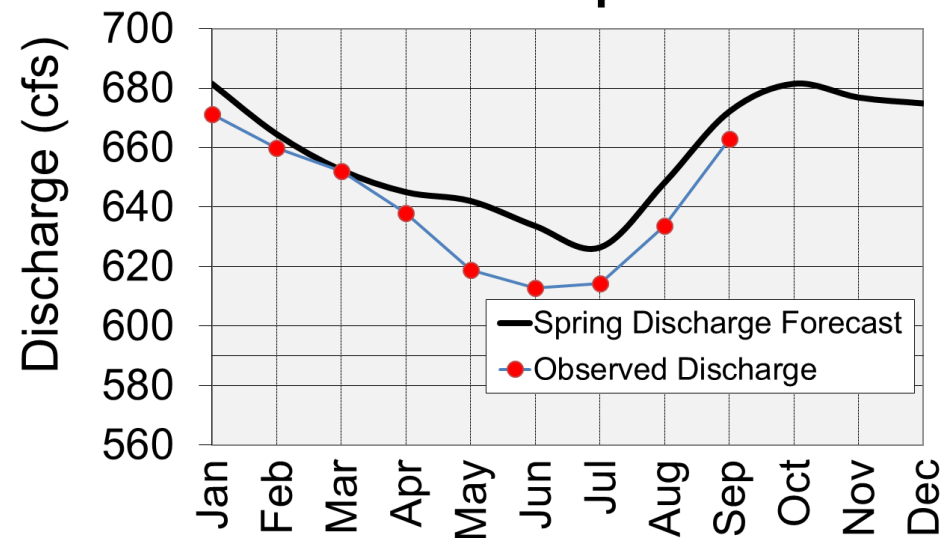
0.5

RUN

### Component Response



### Total Response



# Conclusions

## 1. Analytical

- understand the relationship among lag, attenuation, and distance

## 2. Statistical

- consistent with analytical results
- Developed annual spring Q forecast (applied each April)

## 3. Numerical

- Accurate monthly forecast (applied each January)

Thank you



